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The Vulcano-Glacial Palagonite Formation of Iceland.

By MARTIN A. PEACOCK, B.Sc., Ph.D., Carnegie Research Fellow, University, Glasgow.

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VI. THE VULCANO-GLACIAL PALAGONITE FORMATION OF ICELAND.

I. THE PROBLEM.

THE geological feature which strikes the traveller in Iceland perhaps most forcibly is the complete contrast afforded by the well-ordered, level, or gently dipping basalt sheets with almost negligible tuff intercalations which constitute the Pre-glacial Kainozoic Plateau and the Late-glacial and Recent volcanic formations, and the enormous, chaotic, rarely-bedded accumulations of the Palagonite Formation in which lava flows are subordinate in amount; and he is at once presented with the question: Why did igneous action which produced lava sheets in Pre-glacial times result in dominant tuffs and breccias in the period which followed, and then revert to the production of lavas in later times? This question has not yet been fully answered.

Although the explanation to be offered follows almost as a corollary to Pjeturss' discovery of moraines in the Palagonite Formation (1900), its presentation seems desirable for the following reasons: (1) Pjeturss, whose chief aim was to demonstrate the Glacial age of the formation, did not utilize his discovery to explain the peculiar features exhibited by the igneous rocks associated with it. (2) Whereas the significance of Pjeturss' work does not appear to be fully appreciated, the writings of Thoroddsen are generally regarded as authoritative; but Thoroddsen ascribed a Pliocene age to the major part of the formation, a view which cannot now be entertained, and furthermore failed to provide an adequate theory of its origin. (3) The observations which led the present writer to a vulcano-glacial theory of origin were for the greater part petrographic, and thus of an entirely different nature to those which led Pjeturss to regard the formation as Glacial in age.

II. THE NATURE AND EXTENT OF THE PALAGONITE FORMATION.

1. *Nomenclature.*

The formation whose origin it is proposed to discuss has been variously designated in the geological literature. Bunsen employed the term "*Tuffgebirge*" (1847, p. 265), which was also used by Keilhack in his earlier work (1886, p. 390), while the discovery of wide-spread palagonite throughout the formation initiated the term "*Palagonitformation*" which was generally used by Thoroddsen (1906, p. 287). In addition to these, "Palagonite-breccia Formation," "Tuff and Breccia Formation," and "Breccia Formation" are frequently met. On account of the heterogeneous nature of the formation none of these terms is wholly satisfactory, but, although palagonite appears only as a characteristic accessory in the tuffs, "Palagonite Formation" will be used in the following pages because this name is perhaps most generally used, and because petrographic evidence bearing on palagonite will be adduced to support a vulcano-glacial theory of origin.

2. *Extent of the Formation.*

The Palagonite Formation occupies a broad, irregular belt stretching across Iceland in a S.W.–N.E. direction; it is extensively, although thinly, covered by younger lavas, glacial deposits, and ice, and thus its total area with this covering removed is greatly in excess of its actual outcrop (Fig. 1). The formation, whose base is almost always invisible, builds the highest mountains in Iceland; in many areas it occupies considerable tracts above the 1200 m. contour, as on the Tindfjallajökull, where Dr. Tyrrell and the writer followed the breccia up to 1,305 m. above sea-level. Considering the enormous erosion which the formation has suffered in comparatively recent times, as, for instance, in the great gorge Stóra Valagil, on the W. side of the Tindfjallajökull, we may safely say that it once greatly exceeded its present-day thickness.

3. *The Nature of the Formation.*

The formation is built of breccias, tuffs, palagonite-rock, conglomerates, gravels, moraines, sands, clays, shell-beds and "erratics", together with intrusive basaltic dykes, sills, masses with globular structure, and extrusive basaltic flows. The number of these members and their mutual proportions vary greatly from place to place, and occasionally the formation is represented by the dominant development of only one component.

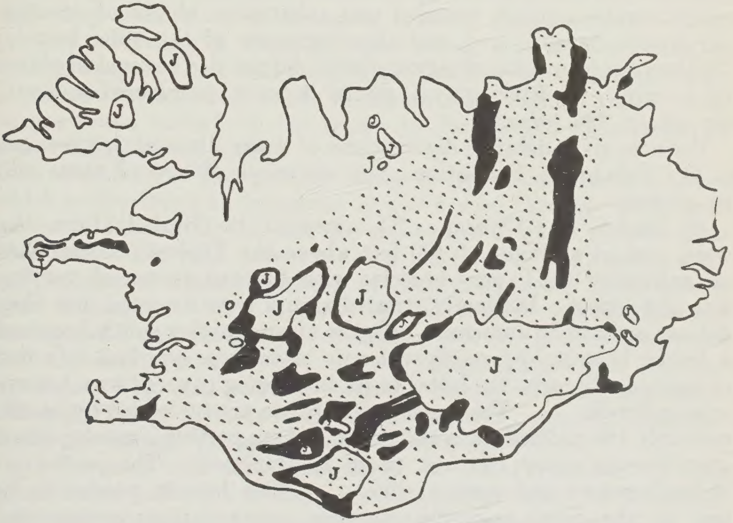

FIG. 1.—Map of Iceland showing in black the approximate exposures of the Palagonite Formation (roughly after Thoroddsen), and the approximate extent of the formation with the cover of younger lavas, superficial deposits and ice removed (dotted). The blank areas to the east and west are occupied by the Pre-glacial, Kainozoic Plateau; the highland ice-fields (*Jökull*) are indicated by the letter *J*.

(*a*) *Vestur Skaptafellssýsla.* Thoroddsen described the breccia mountains in this locality as follows :—" At Sída and Fljótshverfi the mountains are built of brown palagonite-tuff and breccia. Not infrequently one finds in the breccia well-rounded and partly rounded blocks. The steep, wild mountain face of Núpsstadur, which consists for the greater part of tuff and breccia, is held together by a great basalt dyke (S. 40° W.). . . . Fallen blocks, which are 10–20 cub. m. in size, show bedding, and in the palagonitic binding material innumerable rounded stones are found, mixed with many large and small angular stones which have apparently not been involved in any rolling or abrasion process" (op. cit., p. 292, *trans.*).

(*b*) *Hofsjökull.* The same author, in describing the Palagonite formation in the Hofsjökull region, wrote as follows: "The so-called Illvidrahnúkur, on the border of the Hofsjökull, all consist of palagonite-breccia, tuffs, dolerite, conglomerates, and old moraines. . . . The succession appears to be in most cases as follows: (1) Basalt, at the base. (2) Palagonite-breccia with angular lava-fragments. (3) Striated dolerite. (4) Younger breccia and conglomerates with palagonitic binding material. These conglomerates contain rounded and subangular blocks of dolerite, porphyritic basaltic lava, and also fragments of the older breccia. (5) Grey conglomerate of newer glacial debris, also covered in places by dolerite. (6) River gravel, glacial deposits, and loose boulders" (op. cit., p. 296, *trans.*).

Pjeturss gives detailed descriptions of many illuminating sections in the Palagonite Formation; the essentials of two of these will be quoted.

(*c*) *Búrfell, R. Thjórsá.* "I ascended it (Búrfell) from the west, and at a height of 400 feet above the Thjórsá, encountered an extremely hard, grey breccia, with blunted stones of varying size and aspect. Distinctly striated stones were detected, but they did not seem to be numerous. Higher up and farther south I noticed a brown breccia, apparently volcanic, which was overlaid by a bed of morainic breccia, the latter in its turn being covered by a brown-coloured rock. . . . The breccias referred to are succeeded by basalt, probably 150 to 200 feet in thickness, and supporting a much-jointed grey breccia some 100 feet or so in thickness. The joints cut through stones and matrix alike. . . . This breccia proved to be one of the most markedly morainic accumulations encountered in the course of my wanderings. Towards the base it is very stony, with big, blunted blocks, none of which, so far as I saw, showed any distinct striae. A little higher up in the bed, however, any number of striated stones appeared—blocks of a compact, black basalt, exhibiting the finest polish one could wish to see. The rock contained also some boulders of what I took to be morainic breccia of a different colour. A comparatively small portion of the breccia was of a brown colour and contained slightly subangular stones. This brownish-coloured rock reminded me of certain 'palagonite-breccias' which I had supposed were of volcanic origin. On a narrow shelf of basalt, projecting from below the breccia, distinct ice-markings were observed, the direction of the striae being N. to S. There can be no doubt that this characteristic morainic deposit rests upon a striated surface" (1900, p. 283).

(*d*) *Búlandshöfdi, Snaefellsnes.* The section in this locality is particularly interesting on account of the shelly boulder-clay which Pjeturss found reaching to over 600 feet above the sea, in a formation which was previously regarded as entirely volcanic. At about 540 feet above sea-level, resting on the "fundamental basalt" (Pre-glacial Plateau), Pjeturss reports the following succession: (1) Shelly boulder-clay, 70–80 feet, including 10 feet or so of laminated clay. (2) Conglomerate, about 50 feet. (3) A sheet of glaciated, doleritic basalt. (4) Volcanic tuffs and breccias reaching a thickness of 300–400 feet. "The clay is indurated, shows no stratification, and through it are scattered numerous blocks of basalt of various sizes, hardly exceeding, however, 8 inches in diameter. Some of the boulders are angular, others rounded; many, especially the bigger blocks, are so well polished and striated that they could serve as beautiful types of glacier-stones" (1903, p. 358). Writing in 1910, Pjeturss states that at that time 22 molluscan species had been found in the boulder-clay of Búlandshöfdi, of which 20, according to A. S. Jensen, are highly Arctic, such as are found to-day on the coasts of Spitsbergen at a depth of about 30 m. (1910, p. 8).

(*e*) *Seljadalur.* The peculiar facies of the Palagonite Formation which is developed at Seljadalur is well known through the investigation of Bunsen (1847), and the subsequent work of several other observers. The rock here seen is a remarkably pure palagonite-tuff consisting almost entirely of highly hydrous, palagonitized glass fragments. From a study of the various descriptions and micrographs, and the analysis of Bunsen (op. cit., p. 269), it appears that the rock, for which the name "Palagonitfels" was proposed by Bunsen (op. cit., p. 267), compares closely with an explosion-tuff from Videy, S.W. Iceland, which the writer recently described under the name "palagonite-rock" (1926, pp. 455–6).

(*f*) *Intrusive and Extrusive Rocks in the Formation.* "Very considerable intrusive masses are frequently found in the older tuffs and breccias. Compact and slaggy basalt appears in the breccia masses in the form of irregular dykes, innumerable veins, and globular intercalations; it is sometimes present in such amount as to form the main mass of the rock, while the palagonite-tuff acts only as matrix between the countless basalt spheroids and intercalations (Kverkfjöll, Botnssúlur); incidentally the rock has been converted into an irregularly cemented lava-breccia by the intruding basalt. The irregular, nodular, or sausage-shaped basalt intercalations in the breccia are mostly jointed in concentrically arranged columns, and covered by a tachylyte crust; in these cases central cavities are often found" (Thoroddsen, op. cit., p. 289, *trans.*).

In addition to intrusive bodies true lavas are found in the formation. Although Pjeturss frequently does not indicate whether the basalt intercalations in his many sections are sills or flows, it is certain that many of them, e.g. on the Hvalfjördur, are true lavas.

The foregoing extracts may have served to indicate the nature of the Palagonite Formation. Reserving comment, let us pass to a brief review of the various opinions which have been held concerning the age and the origin of the formation.

III. THEORIES REGARDING THE AGE OF THE PALAGONITE FORMATION.

With the progress of geological investigation an ever decreasing antiquity has been ascribed to the Palagonite Formation. Bunsen and his contemporaries believed that the formation was older than the Pre-glacial Kainozoic Plateau (Bunsen, op. cit., p. 265), and even Keilhack, in his earlier work, adhered to the belief that the major part of the formation was early Miocene in age (op. cit., p. 390). The chief difficulty in determining the relative ages of the Palagonite Formation and the Miocene Plateau is the fact that the base of the former is nearly always invisible; even in Snaefellsnes, where the underlying basalt is seen, this basalt, in which surtarbrand intercalations have not been found, cannot be correlated with the Miocene with absolute certainty. There can be no doubt that the researches of Thoroddsen have yielded the true order, which is: (1) The Miocene Plateau. (2) The Palagonite Formation. (3) The striated Grey Basalts (Doleritlava). (4) The Post-glacial and Recent lavas. Fig. 2 expresses this order, and further, it embodies Thoroddsen's view of the Palagonite Formation resting on the centrally down-faulted and foundered Miocene Plateau, and the fact that the Grey Basalts were poured out on the low ground produced by the subsidence of great faulted blocks of the Palagonite Formation, as emphasized by Pjeturss (1900, pp. 266–7).

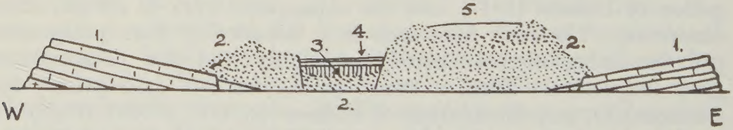

FIG. 2.—Diagrammatic East to West section across Iceland. 1. The Miocene Basalt Plateau, centrally down-faulted and foundered. 2. The Palagonite Formation built on centrally foundered plateau. 3. The striated Grey Basalts (*Doleritlava*), overrunning the lowlands produced by the subsidence of blocks of the Palagonite Formation 4. Post-glacial and Recent lavas. 5. Present-day ice-fields (*Jökull*).

Before 1900 the only glaciation of Iceland recognized was the one following the eruption of the Grey Basalts; and hence Thoroddsen termed these rocks "Pre-glacial", and ascribed to the older Palagonite Formation a Pliocene age. The researches of Pjeturss have shown, however, that this glaciation represented only the last phase of the Glacial Epoch, and that the records of the earlier glaciations are buried in the Palagonite Formation.

In his geological map (1901), published after Pjeturss' first report of the discovery of moraines in the Palagonite Formation (1900), Thoroddsen made a partial concession by indicating the Grey Basalts as " Glacial and Pre-glacial doleritic lavas ". Pjeturss' evidence in the various papers quoted makes it clear that the Grey Basalts everywhere overlie rocks which record earlier glaciations. " Pre-glacial " cannot therefore be applied to the Grey Basalts. It cannot yet be definitely decided whether these rocks were erupted during a Late-glacial retreat, or during an actual Late-interglacial interval ; the extent of these lavas and their non-contamination with glacial material seem to indicate that their eruption took place under the latter conditions, and that therefore these rocks should be considered Late-interglacial in preference to Late-glacial.

All the available evidence points to the Glacial or Early-glacial age of the Palagonite Formation ; not only do the writings of Pjeturss, whose object was to establish this point, afford definite proof, but passages may be found in the writings of the earlier observers, who believed in the much greater antiquity of the formation, which lead to the same conclusion. Take for instance the following observations of Keilhack, written at a time when he believed in the early Miocene age of the formation. " In many places in S. Iceland true conglomerates are found in the Miocene (Palagonite Formation) with blocks exceeding a cubic foot in size. The structure of these coarse masses is remarkably reminiscent of that of the Icelandic moraine formations. One sees blocks of all sizes confusedly embedded in a finer, compacted matrix ; and so closely does their structure resemble the recent terminal moraines, that only when one considers the tachylytic binding material of these conglomerates, and the hundreds of meters of overlying basalts and tuffs, can one avoid thinking that these wholly structureless masses are the products of glacial action. Furthermore, the individual blocks of these conglomerates in no wise display the characteristic surface features of volcanic ejecta " (op. cit., pp. 384–5, *trans.*). Does not the tachylytic binding material of these " conglomerates ", and the superincumbent volcanic pile point rather to the co-operation of glaciation and vulcanism ? [1]

Again, Thoroddsen expresses a similar dilemma in the following words : " In extended sections numerous, great, angular blocks are frequently found irregularly distributed over large areas, and it is not easy to picture the manner in which this distribution took place ; provided that these blocks were ejected by volcanoes, it would appear that the explosions of the past were incomparably more powerful than those of the present " (op. cit., p. 290, *trans.*). Rather than resort to excessive explosive violence, would transport by ice not provide a readier means of effecting this extended distribution of large blocks ?

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[1] Since this was written the appearance of Dr. Keilhack's paper with a geological map of the Reykjavík district (1925) makes it clear that Dr. Keilhack is now in full accord with Dr. Pjeturss' view of the Glacial age of the Palagonite Formation.

One point remains to be considered : the Glacial Epoch in Iceland was undoubtedly a protracted one, and one cannot be sure that it did not commence in late Pliocene times. A full investigation of the fossiliferous sediments at Tjörnes, N. Iceland, where Crag deposits are found together with fossiliferous glacial sediments and igneous rocks, might prove that this was actually the case ; and thereby, without affecting the main issue, namely the Glacial age of the Palagonite Formation, Thoroddsen's conception of a Pliocene age would regain a partial measure of truth.

IV. THEORIES REGARDING THE ORIGIN OF THE PALAGONITE FORMATION.

The earlier observers were of the opinion that the Palagonite Formation was submarine in origin. In adopting this theory Sartorius v. Waltershausen and Bunsen were partly guided by the necessity for providing special conditions of eruption to account for the peculiar features presented by the plentiful palagonite which they found in the tuffs of the formation ; and they were apparently confirmed in their belief by the discovery of marine shell fragments associated with the palagonite tuffs. With the exhaustive work of Penck (1879), who concluded that " a substance to be called palagonite does not exist ", and that the material which had previously been described in tuffs as palagonite was simply a mixture of dominantly vitreous, basaltic ejecta, together with their alteration products and binding material (op. cit., p. 568), palagonite was reduced from its previous exalted rank as a distinct mineral species with a chemical formula proper to itself, and the necessity for providing special conditions for its formation was apparently removed.

In dismissing the submarine theory Thoroddsen endeavours to show that the three main arguments which were advanced to support it are actually invalid. These arguments are that the tuffs are always bedded ; that they contain shells ; and that palagonite is not found in the products of historic volcanoes. Thoroddsen tells us that the tuffs are not always bedded, and that even where they are the bedding may be due to the action of wind rather than water. As to the presence of shells, Thoroddsen states that these shell-beds belong to the Glacial and Post-glacial terraces, which are seldom found higher than 70 m. above sea-level, and that therefore the palagonitic material is not in its original situation. With regard to the third point, Thoroddsen states that the absence of palagonite in the modern eruptives is by no means certain, and furthermore, being a decomposition product, its presence would not be expected in these younger rocks (op. cit., p. 291). To Thoroddsen's reasons for rejecting the submarine theory might be added the fact that the Palagonite Formation exceeds 4,000 feet to-day, and once probably greatly exceeded this thickness, and that there is nowhere evidence of a submersion of corresponding extent.

Without advocating the submarine theory, it might be pointed out that Thoroddsen's reasons for rejecting it are not wholly satisfying. Pjeturss' shelly boulder-clay at Búlandshöfdi must be regarded as evidence of submersion of about 600 feet. Also, granting that palagonite is a secondary product, and therefore not to be expected in recent eruptives, is it not surprising that this material is not found in comparable condition and amount in the tuffs of the Miocene Basalt Plateau ?

Having rejected the submarine theory, Thoroddsen writes :—" There is therefore no necessity to assume that the formation of tuffs and breccias was formed in any other way than by eruptions on dry land " (loc. cit., *trans.*).

Keilhack's view of 1886 agrees practically with that of Thoroddsen ; speaking of the conglomerates in the Palagonite Formation, Keilhack, without absolutely excluding the possibility that they might have been formed on the borders of a shallow sea, expresses the opinion that they are more probably fluviatile in origin (op. cit., p. 385).

V. THE PALAGONITE SERIES ON VIDEY, S.W. ICELAND, AND THE SUB-GLACIAL EXTRUSION HYPOTHESIS.

At the commencement of the geological expedition to Iceland in 1924, which was conducted by Dr. G. W. Tyrrell and the present writer, aided by a grant from the Carnegie Trust, the author took advantage of his earlier arrival in Iceland by devoting his time to a detailed survey of Videy, a small island which lies 3 miles E.N.E. of Reykjavík. From the fuller account of this work (1926) some data will be extracted bearing on the problem under discussion.

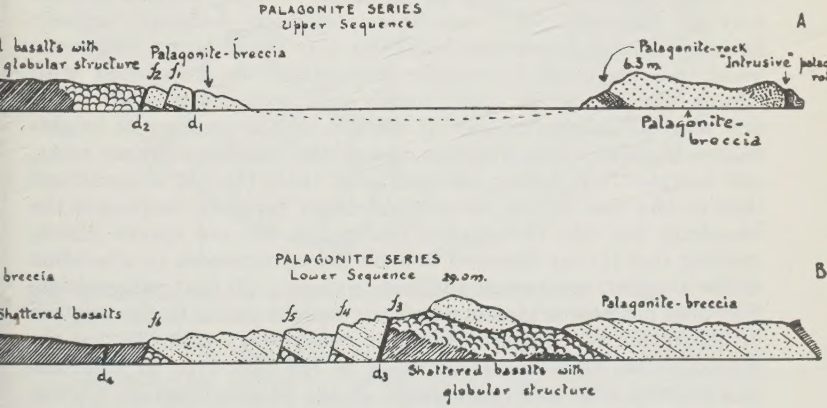

FIG. 3.—S.E.–N.W. section along the S.W. shore of Videy, S.W. Iceland ; the total length of the section (A to C) is about 1 km.

The elevated belt which borders the S.W. shore of Videy is composed of palagonite-breccia, conformably underlain by fine-grained, intrusive, globular basalt; the series is extensively faulted, and copiously intruded by doleritic and basaltic dykes (Fig. 3).

The breccia consists of black, vitreous fragments which grade in size from 1½ cms. downwards, and are cemented by their own palagonitization products; it also contains, in varying amounts, foreign, angular, basaltic blocks which range from first-size to 4 feet in diameter. The globular basalt, which agrees in appearance with Thoroddsen's description of globular intrusions in the Palagonite Formation (quoted on pp. 378–9), is characterized by the spheroidal structure which is associated with "pillow-lavas"; as the Videy examples are intrusive in character the term "pillow-lava" has been avoided in favour of "globular basalt" which was used by Johnston-Lavis to describe similar rocks at Reykjanes, S.W. Iceland (1895, p. 445). No xenoliths were observed in the globular basalt; as the palagonite-breccia was regarded as the surface facies of the globular intrusion, this absence of xenoliths in the latter was taken as proof that the blocks in the breccia were not carried up from below, but were derived from above.

A specimen of the palagonite-breccia, taken near C (Fig. 3), yielded the following data. In section (Fig. 4), the vitreous fragments which constitute the rock are seen to possess neither the high degree of vesicularity, nor the "Aschenstruktur" of typical tuffs; instead, the particles are bounded by smooth curves (the traces of conchoidal fracture), and are only negligibly vesicular. Three types of fragments may be distinguished: pale-brown, slightly vesicular, entirely homogeneous and isotropic fragments (1); dark-brown fragments which are traversed by opaque flow-bands, or are dotted with minute ore specks (2); and totally opaque tachylytes (3). The first stage of palagonitization is marked by the presence of bright-yellow, bleached borders surrounding all the translucent glassy areas, and completely replacing the smaller of these (4). It is significant that in the case of the second and third types of fragments the bleaching has left the opaque bands and the ore specks intact, proving that (1) the bleached borders indeed represent an alteration of the margins, and not an addition to them; (2) that palagonitization does not attack glasses which are opaque owing to the solution or separation of magnetic iron (i.e. tachylyte); and (3) that the homogeneous, translucent condition of the first type of fragment is a primary one, and not a result of the palagonitization process. The outer borders of the bleached margins pass into a finely-fibrous yellow-red, birefracting mineral of the goethite type (Fig. 4, (5)) while the remaining interspaces are filled by a zeolite (6) which has optical and chemical characters indicating that it may be an impure potash analogue of analcite.

It was shown that palagonitization proceeded only in the case of primarily translucent basaltic glasses, and in seeking for a cause for this condition of the glass a primary, abnormally high, water content at once suggested itself. To verify this, a piece of the specimen was coarsely ground, and small chips, which showed by their clean, lustrous surfaces that they were derived from the unaltered cores, were separated; on ignition they lost 4·38 per cent. As the average H_2O content of four "superior" analyses of tachylyte given by Washington (1917) is 1·13 per cent, it was evident that the translucent glass differed from tachylyte in possessing a much greater H_2O content, and that therefore it might appropriately be designated "hydrotachylyte". From the above it appeared that palagonitization does not take place in the normal, almost anhydrous tachylytes which are characteristically opaque owing to the solution or separation of magnetic iron oxide, but attacks only

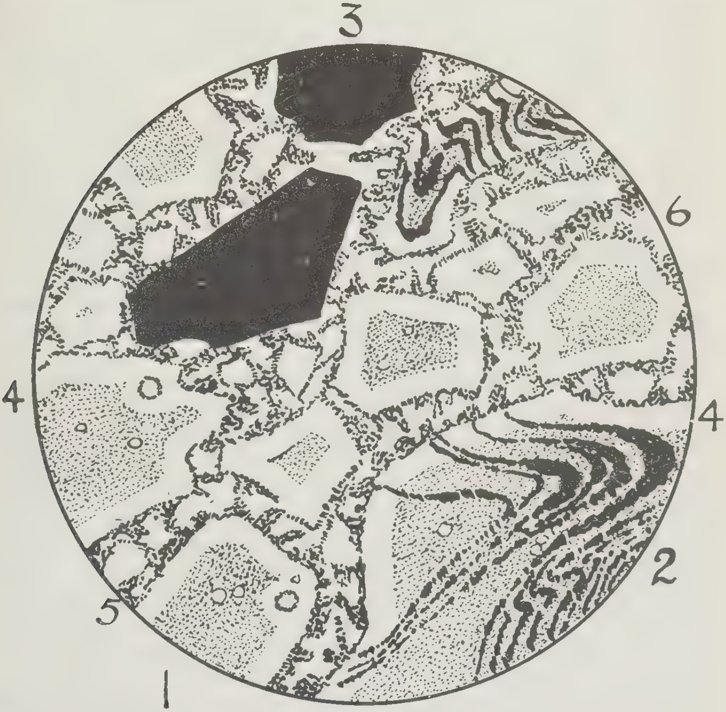

Fig. 4.—Micrograph of palagonite-breccia collected near C, Fig. 3, Videy, S.W. Iceland, magnified 14 diameters. 1. Pale-brown, translucent hydrotachylyte. 2. Dark-brown hydrotachylyte traversed by opaque flow-bands. 3. Tachylyte. 4. Bright-yellow bleached borders of the hydrotachylyte fragments, representing the first stage of palagonitization. 5. Mineral of the goethite type growing from the bleached borders. 6. Zeolite filling interspace.

hydrous, translucent basaltic glasses which may be termed "hydrotachylyte".[1]

Finally, the Videy palagonite series was correlated with similar rocks at Botnsvogur (Hvalfjördur), and Gullfoss, in both of which localities evidence of Glacial age was obtained. With the strong presumption that the Videy palagonite series was therefore also Glacial in age, an attempt was made to explain its various features by postulating *sub-glacial extrusion* as its mode of origin. By assuming that a basaltic magma found limited egress at the base of a massive ice-sheet which, by virtue of its thickness and mechanical strength, was capable of resisting disruption, conditions were apparently found which satisfactorily accounted for the peculiarities of the palagonite series.

(1) The foreign, angular, basaltic blocks in the palagonite-breccia which, it was inferred, were derived from above, were considered to have been released from the base of the ice-sheet by the vaporization of the ice in the neighbourhood of the intrusion.

(2) The production of hydrotachylyte, with its full initial H_2O complement retained in solid solution, was explained as the result of the combined chilling and restraining effect of the superincumbent ice-sheet; the shattering of the intruded hydrotachylyte into fragments which were negligibly vesicular, and free from *Aschenstruktur*, was referred to the same cause.

(3) The globular structure in the rock underlying the palagonite-breccia was considered to be due to the further extrusion of basaltic magma into the previously formed hydrotachylyte tuff-bed, which, owing to a temporary abeyance of the extrusive paroxysm, had become waterlogged. In this way the conditions which are known to produce pillow or globular structure, namely, rapid chilling accompanied by the urging forward and feeding of the extruded mass by further liquid supply, were realized.

VI. The Vulcano-Glacial Palagonite Formation of Iceland.

Let us now consider more generally the effects of glacial conditions on the products of volcanic action in Iceland. The comparative rarity of associated palagonite-breccias and globular basalts of the Videy type indicates that the special conditions of sub-glacial extrusion postulated to explain these rocks only rarely obtained, and that therefore the more general case of sub-glacial extrusion was one in which the extrusive energy exceeded the restraining capacity of the overlying ice, and an eruption resulted, producing fragmented, anhydrous sideromelan. Sub-glacial eruptions have taken place in the inaccessible interiors of the great ice-fields in historic times; they have caused catastrophies, called Jökullhlaup, in which the melting of parts of the ice-sheets resulted in floods of water which carried down and deposited indiscriminately volcanic and glacial material. In addition to these two glacially modified forms of volcanic activity normal lava production undoubtedly took place to a limited extent during the major glacial retreats. Assuming that vulcanicity of these three types ensued during the Glacial Period, and bearing in mind that in one locality at least the land has emerged since Glacial Times to the extent of 600 feet, we can apparently account for those geological features which distinguish the Palagonite Formation from both the older and the younger formations of Iceland.

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[1] Further petrographic study of the palagonite-tuffs has shown that the translucency of the basaltic glasses which suffer palagonitization cannot always be related to a high primary water-content, and that therefore these glasses are best designated by v. Walterhausen's term "*sideromelan*". The writer is now convinced that the translucency of sideromelan is purely the result of the drastic chilling which this material suffered on extrusion.

The Restriction of Palagonite to the Formation. Although the thin tuff partings of the Miocene Plateau contain palagonitized vitreous fragments, the palagonitization which these fragments show is neither advanced nor characteristic, in the writer's experience; in amount, also, the palagonite of the Miocene is negligible in comparison with that of the Palagonite Formation. As palagonite has not been found in the Recent eruptives (p. 392), it is thus practically restricted to the Palagonite Formation. The absence of palagonitization in normal, opaque, almost anhydrous tachylyte lends support to the writer's contention that palagonitization attacks only sideromelan, and thus, granting this contention, if glacial conditions will explain the production of sideromelan, the restriction of palagonite to the Palagonite Formation will follow as a corollary.

The retention in solid solution of notable amounts of magmatic water in hydrotachylyte, and the inhibition of the separation of ores, which is the basic cause of the translucency of sideromelan, could be caused only by the excessively rapid chilling such as would be produced by the contact of the extruded magma with water or ice. Although submarine eruptions are known to have occurred off the shores of Iceland in historic times, the production of sideromelan by means of these is regarded as relatively unimportant for the following reason. The 600 feet emergence at Búlandshöfdi (p. 388) is an extreme and isolated case and even granting that the sea generally attained that level in Glacial Times six-sevenths of the Palagonite Formation were certainly never submerged. Land-water and ice thus appear to have been the chief agents in the production of sideromelan. Fluvio-glacial waters may have contributed to a limited extent, but the ice-sheets and the glaciers themselves were doubtless the principal sideromelan-producing agents; thus the restriction of palagonite to the Palagonite Formation may be explained.

Intrusions with Globular Structure. These also are peculiar to the Palagonite Formation. Thoroddsen has noted them in many localities (op. cit., pp. 289–90), and the writer has observed them invariably associated with palagonite-breccia on Videy, and at Reykjanes, Botnsvogur, and Gullfoss; this invariable association leads him to think that the production of globular structure is also a result of the modifying influence of glacial conditions on volcanic action. Globular structure has not been observed in the basalts of the Miocene Plateau, or in the recent lavas of Iceland. This structure is known to be induced by the extrusion of a magma into chilling and only gently resisting materials, such as waterlogged sediments or tuff-beds, water, or even rain-laden air. Johnston-Lavis expressed the opinion that the Reykjanes globular basalts represented the ruin of a submarine cone (1895, p. 445); although the low level of this locality, and of the other localities mentioned (with the exception of Gullfoss, where the globular basalts lie 690 feet above sea-level) seem to indicate that the rocks in places were formed by submarine extrusion, the writer is disposed to think that they were formed by extrusion into waterlogged, sub-glacial hydrotachylyte tuff-beds, as suggested above, for the following reasons: (1) The globular basalts of Videy, Reykjanes, and Botnsvogur are in down-faulted parts of the old Palagonite Formation plateau, and therefore their present position near sea-level is no proof of submarine origin; in view of this down-faulting it is rather probable that these globular basalts originally lay on the horizon of the Gullfoss example. (2) The constant association of globular basalt with palagonite-breccia indicates that, if sub-glacial extrusion produced palagonite-breccia, globular structure is also to be referred to the modifying influence of glacial conditions. (3) Occlusions of marine sediments have not been found between the individual spheroids of the globular masses.

The remaining peculiarities of the Palagonite Formation are readily explicable on the basis of a vulcano-glacial theory of origin, and require little comment. The interpretation of the palagonite-breccia with rounded stones and angular stones, Thoroddsen's description of which was quoted on p. 288, presents no difficulty; the presence of widely-distributed striated stones throughout the formation occasions no surprise; and the widely-spread, large, angular blocks, which could otherwise be ascribed only to excessive explosive violence become ice-borne blocks which were incorporated in the products of a sub-glacial volcano.

In conclusion the writer would record his indebtedness to Dr. G. W. Tyrrell, in conjunction with whom the visit to Iceland was conducted, and with whom the views and arguments of the foregoing pages were frequently discussed to their material improvement.

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The Igneous Complex of Green Island and the Amherst Coast (Lower Burma).[1]

By Professor L. Dudley Stamp, B.A., D.Sc., A.K.C., F.G.S.,
University of Rangoon.

(PLATE XXVII.)

CONTENTS.

I. Introduction.
II General Sketch of the Geology.
III.. Petrology.
IV. Tectonics.
V. Summary.

I. Introduction.

THE great Salween River enters the sea by two mouths, one to the north and one to the south of Bilugyun Island. The southern branch is the more important and serves as a means of approach to the old port of Moulmein. Vessels bound for Moulmein pick up their pilot from the village or little town of Amherst, whilst just to the south the light from the Green Island lighthouse (erected in 1902) sends warning of the numerous dangerous reefs near by. For from Amherst southwards the coast is rocky and fringed with reefs, whilst northwards mud flats with mangrove swamps are the rule.

The writer spent the Christmas vacation of 1924 on the delightful stretch of coast at Amherst. So far as he is aware, nothing has been written concerning the geology of the region, and naturally it was of interest to get a rough idea of the local geology. The most cursory examination, however, showed that Green Island and the adjacent coast presented features of far more than local interest, and the investigation was continued both in field and laboratory with the results outlined below.

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[1] Paper read before the section of Geology of the Indian Science Congress, Bombay, 1926.

The microscopical investigation has been carried out partly in the University of Rangoon and partly in the University of London, King's College. The writer wishes to express his thanks to Dr. A. K. Wells, with whom the petrology has been discussed and to Mr. S. W. Wooldridge, who also examined some of the microsections.

II. General Sketch of the Geology.

The Amherst coast enjoys a rainfall of nearly 200 inches a year, practically the whole of which falls during the " rainy season " between May and November. Such conditions are markedly conducive to the formation of laterite, a thick mantle of which obscures the inland geology. The sea coast, therefore, affords invaluable evidence. In the area studied the low cliffs are usually of laterite, but the numerous reefs exposed at low tide afford admirable exposures.

The normal strike of the district is S.S.E.–N.N.W. Comparatively unaltered country rocks are seen at Amherst itself and may be described as slightly altered grey or black shales, not unlike the softer varieties of the " Killas " of Cornwall. Quartz veins occur in these rocks, usually coincident with the bedding, but sometimes transgressive. As one goes westwards the quartz veins become more numerous and amongst them appear other veins of coarse muscovite-quartz pegmatite. Like the quartz veins, the pegmatite veins usually coincide with the bedding but are of inconstant thickness. With the appearance of the pegmatite veins, metamorphism of the country rock becomes marked and the place of the shales is taken by soft mica schists. Passing still further westwards, that is downwards in the sequence, veins of quartz-felspar rocks take the place of the pegmatites and quartz veins and the metamorphism of the country rocks becomes more noticeable, hard mica schists being the dominant type. The next stage seems to be the development of typical lit-par-lit injection—of acid rocks approaching granite in composition into mica or mica-hornblende schists. This stage may be easily studied at the northern end of Green Island or southern end of Pagoda Bay. As with the pegmatites, the granitic veins as a general rule follow the bedding, but in places are definitely transgressive, they are also seen to swell out or thin and tail out or to coalesce and in places connect with small intrusive masses of irregular shape. These developments are well seen at the northern end of Green Island. Passing downwards in the sequence the inter-relationships between the invading and invaded rocks become more and more intimate, the lit-par-lit structure being on a much finer scale and giving rise to a gneissose rock. This in turn passes to a more normal igneous rock, occupying the whole of the reef to the south-west of Green Island. This rock has obviously been contaminated by

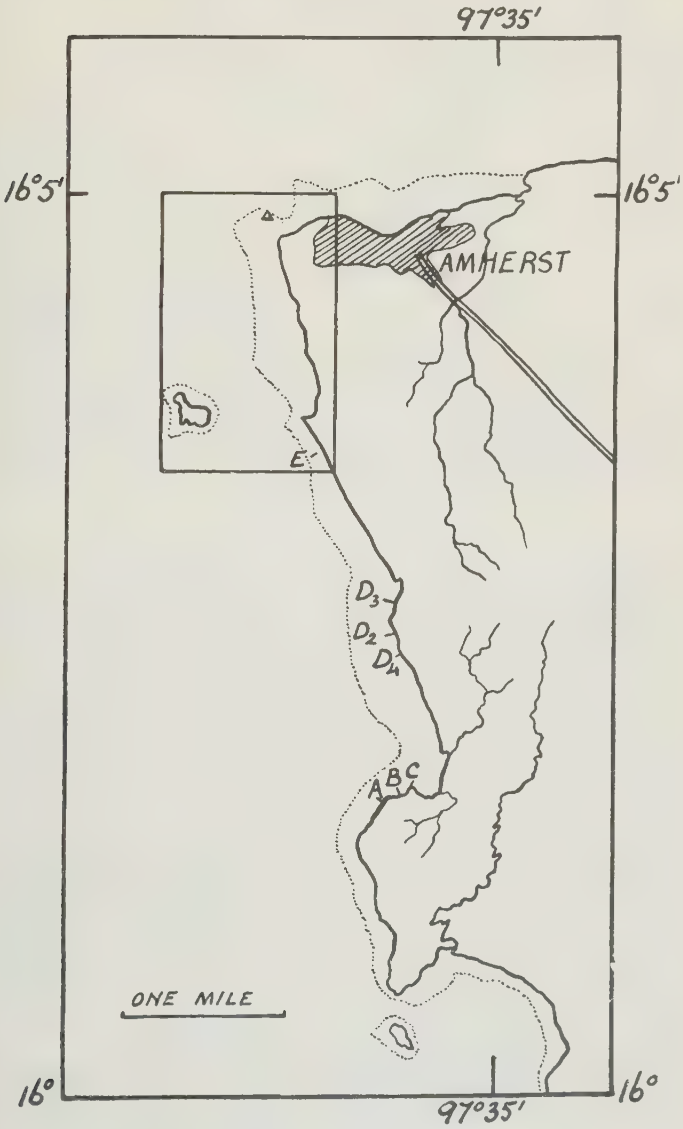


FIG. 1.—Index-map of the coast near Amherst (Lower Burma). The small rectangle shows the area covered by Fig. 2.

absorption of the country rock. Large xenoliths of biotite-hornblende schist, in various states of digestion, are seen. As will be described below, one of the most interesting features is the invariable development of a pale-coloured reaction zone 6 inches or a foot in width, between the dark, almost black xenolith and the dark mica-granite.

Similar features are seen on the mainland, but as one passes southwards the granite becomes more and more normal in general character.

Under the microscope all the igneous rocks agree in possessing a curious shattered character to be described below.

III. PETROLOGY.

There can be little doubt that all the igneous rocks in the area belong to one period of intrusion. Petrographically there is a continuous series from granites, through contaminated granites, intrusion gneisses, granite aplites to pegmatites and quartz veins. The whole series is characterized, microscopically, by the mylonized appearance in section and the micropoikilitic relationships of quartz and the felspars. Although the series is a continuous one, for convenience in description the types present have been roughly grouped under the headings given below.

A. *Granites.*

The forest-covered hills which rise conspicuously some three or four miles south of Amherst and which reach the coast as picturesque rocky headlands consist almost entirely of granite. The coast section was roughly examined as far south as the point A marked on Fig. 1. From A northwards to E the dominant rock is granite.

Macroscopic Characters.—The granite is medium grey in colour, weathering yellow, of even grain, and all the minerals are essentially allotriomorphic. The macroscopic character of the rock is somewhat deceptive, for dark minerals appear more abundant than they really are and in the field one would be tempted to name the rock a granodiorite. Acidic and basic veins are both common in the mass of the granite, and "heathen" are frequent. In the boulders which occur above high water mark two types of weathering are conspicuous. In the one case the surface becomes furrowed by a series of cracks at right angles, so that the surface of the rock exactly resembles a brick wall in which the mortar has worn away. The other type is the ordinary "onion" weathering (on a much larger scale than in the case of dolerites in England) common amongst granites in tropical regions.

Microscopic Characters.—The rock is a fairly coarse biotite-granite. In slides (AM 2, AM 31, AM 19) of typical specimens from the localities marked A and C on Fig. 1, the only dark minerals present are biotite and a little magnetite. The remainder of the rock consists of quartz and felspars forming an irregular interlocking

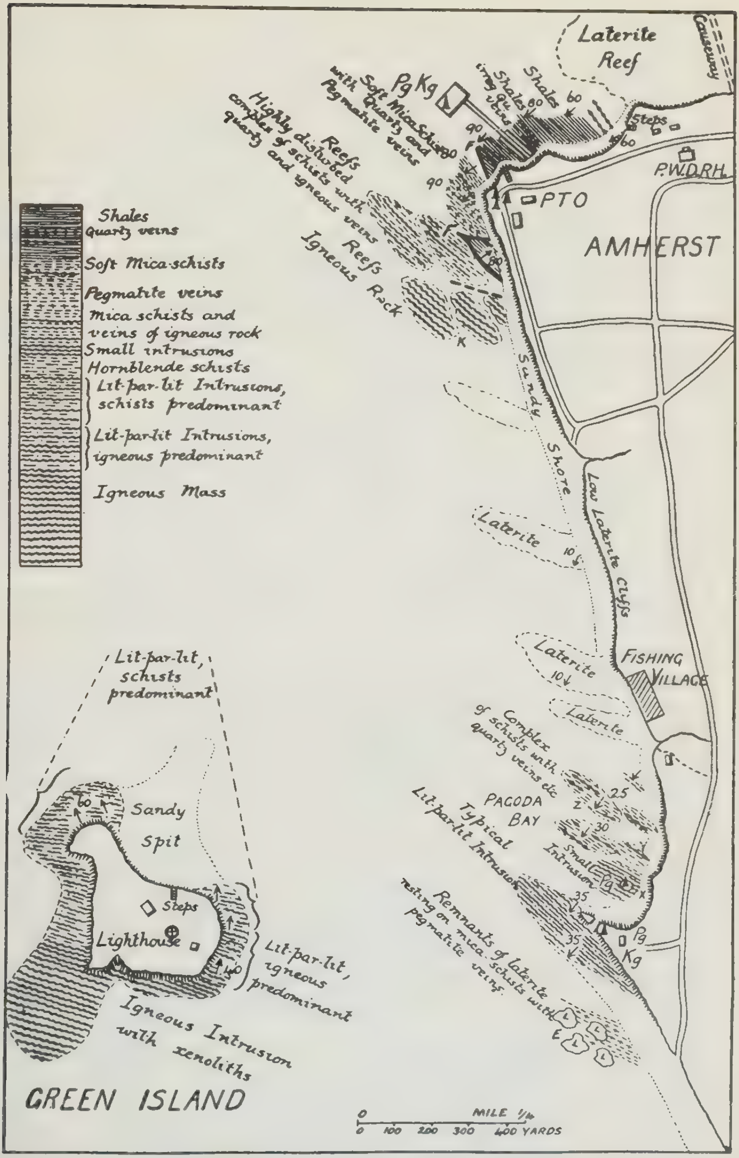

Laterite Reef
Causeway
Shales
Shales
60
Pg Kg
with Soft Mica Schists with Quartz and Pegmatite veins
Reefs
Highly disturbed complex of schists with quartz and igneous veins
Reefs
Igneous Rock
90
60
Steps
P.W.D.R.H.
PTO
AMHERST
Shales
Quartz veins
Soft Mica-schists
Pegmatite veins
Mica schists and veins of igneous rock
Small intrusions
Hornblende schists
Lit-par-lit Intrusions, schists predominant
Lit-par-lit Intrusions, igneous predominant
Igneous Mass
Sandy Shore
Laterite
10
Low Laterite Cliffs
Laterite
10
FISHING VILLAGE
Laterite
Complex of schists with quartz veins etc
25
PAGODA BAY
30
Typical Lit-par-lit Intrusion
Small Intrusion
Pg
35
35
Pg
Kg
Remnants of laterite resting on mica schists with pegmatite veins
Lit-par-lit, schists predominant
Sandy Spit
60
Steps
Lighthouse
40
Lit-par-lit, igneous predominant
Igneous Intrusion with xenoliths
GREEN ISLAND
MILE 1/4
0 100 200 300 400 YARDS

FIG. 2.—Geological sketch-map of Green Island and the coast at Amherst (Burma).—*L. Dudley Stamp.* Pg = Pagoda; Kg = Monastery; PTO = Post Office; RH = Rest House.

mosaic. The larger grains or groups of grains are interrupted by what at first sight appears to be a very much finer mosaic of the same minerals. It is found, on examination, however, that groups of the smaller grains extinguish together and that the finer mosaic consists of quartz and felspar micropoikilitically intergrown. Apart from the irregular outlines which characterize all the minerals the quartz does not show any special features. The most abundant felspar is orthoclase, slightly cloudy but otherwise unaltered. Twinning of the orthoclase is exceptional. There are considerable proportions of perthite, often grains rather larger than the average, an acid plagioclase with narrow twin lamellae and a little microcline. All the felspars tend to show slightly undulose extinction and other features associated with strain. The micropoikilitic intergrowth appears to be mainly of quartz and orthoclase. A little muscovite is usually present.

B. *Contaminated Granites.*

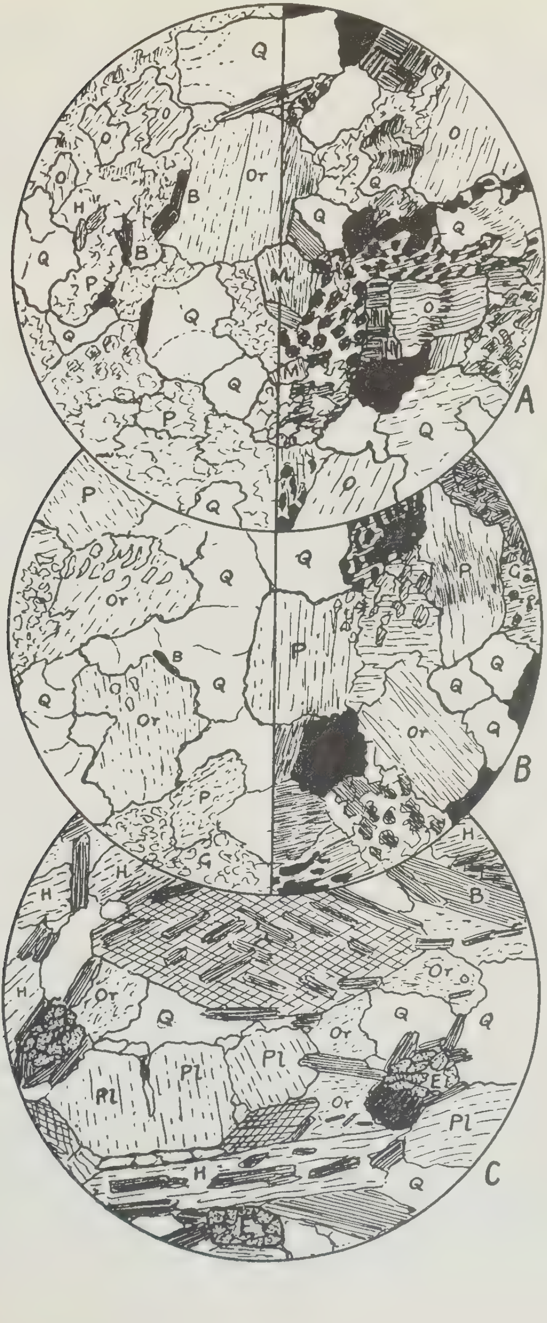
The largest mass of granite which may be regarded as "contaminated" by extensive assimilation of country rocks is that exposed at the southern end of Green Island. Similar rocks form small intrusions (as in Pagoda Bay, where a huge boulder of the rock, surrounded by water at high tide, is surmounted by a small pagoda) and at the northern end of Green Island.

Megascopic Characters.—When compared with the more normal granite, the present rocks are darker in colour owing to the larger content of biotite.

Microscopic Characters.—Under the microscope these rocks are very similar to the granites described above. Biotite is slightly more abundant. Amongst the colourless minerals, it was suspected that small quantities of cordierite occurred. Repeated examination of thin sections, thicker sections and of crushed material has shown, however, that this mineral is not present.

Xenoliths in the Contaminated Granites.—The contaminated granite is magnificently exposed at low tide at the southern end of Green Island. One of the most interesting features is the large number of xenoliths of the country rock. The xenoliths range from huge blocks showing the bedding of the ordinary mica-schist, through irregular-shaped masses of various size, down to small fragments almost completely assimilated. The smaller xenoliths (section

FIG. 3.—Microsections of typical rocks. A = Normal Granite, south-west of Green Island (AM 37), more than 10 feet from a xenolith; right half under crossed nicols. Notice the mylonitic structure, abundant intergrowths, and the strain shown by felspars and quartz. B = White Reaction Zone (Granite Aplite), southern end of Green Island (AM 49); right half under crossed nicols. C = Typical xenolith, in ordinary light, southern end of Green Island (A M58). Q = Quartz; Or = Orthoclase; P = Perthite; Pl = Acid plagioclase; G = Graphic intergrowth of quartz and felspar; M = Muscovite; B = Biotite; H = Hornblende; E = Epidote.


Q
O
O
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Or
O
Q
H
B
B
Q
Q
Q
P
M
Q
Q
O
M
Q
P
Q
Q
A
P
Q
Q
P
G
Or
Q
B
Q
Q
Or
P
Q
Q
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H
H
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Or
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E
Or
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H
Q
C

AM 58) are greenish-black in colour and appear to consist of a mixture of biotite and hornblende. A closer inspection reveals the presence of mafic minerals. Under the microscope femic and mafic minerals are seen to be present in roughly equal proportions. The former include hornblende and biotite, equally important. Small flakes of biotite are often seen enclosed in larger crystals of hornblende (Fig. 3, C). A considerable amount of epidote is present either as subidiomorphic crystals or granular aggregates. There are a few small crystals of apatite. The mafic minerals include an acid plagioclase, microcline, and a little orthoclase, together with a moderate amount of quartz.

When the xenoliths are very rich in femic minerals—biotite and hornblende—and the magma is comparatively poor in these minerals, one would naturally expect to find the xenoliths surrounded by a reaction zone comparatively rich in biotite or hornblende or both. On the contrary, each xenolith is surrounded by a reaction zone, usually from 6 to 8 inches in width, in which dark minerals are almost entirely absent. In the field, therefore, the black xenolith is separated from the grey granite by a white band. Fig. 4 is a tracing from an actual photograph taken by the writer illustrating this point. The rock of the reaction band may best be described as a *granite-aplite*. Under the microscope (AM 30) it is found that the most abundant mineral is orthoclase. Acid plagioclase and microcline occur as in the granites, but there is much less quartz. A few small scattered flakes of biotite are seen and a few grains of epidote, but otherwise femic minerals are absent. It will be seen

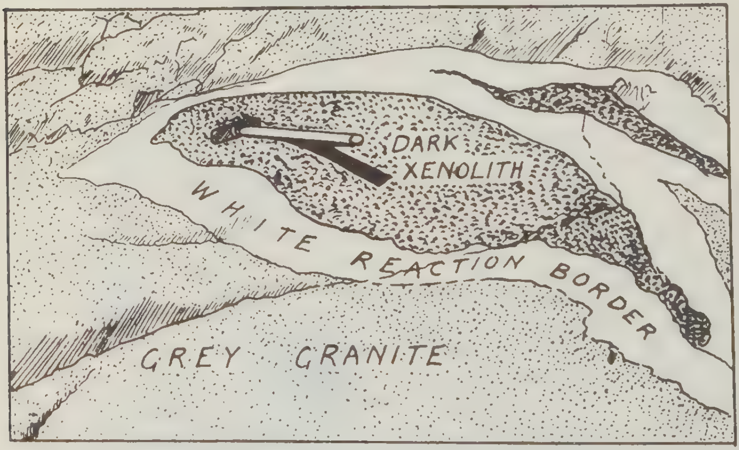

Fig. 4.—Tracing from an actual photograph, showing the white reaction border between the grey granite and the dark-coloured xenolith. Southern end of Green Island.

at once that this pale-coloured border cannot represent a portion of the magma enriched by complete absorption of the mica-hornblende schists of the xenoliths. It would seem that there has been a definite exchange of material between the xenoliths and the granitic magma, the xenoliths having become enriched in iron and magnesia whilst the adjacent layers of the magma received alkalis and a little lime. It will be noticed that the reaction zone is richer in acid plagioclase but poorer in quartz than the normal granite. Thus the free quartz of the granite appears to have combined with soda and lime from the xenoliths.

C. *The Intrusion Gneisses.*

These rocks are particularly well seen on the western side of Green Island. In the field they look exactly like fine-grained acid gneisses of metamorphic origin. Southwards, however, they fade gradually into the contaminated granite mass just described, whilst to the north they give place gradually to normal lit-par-lit injection of granite-aplite in schist. Seen in the field the streakiness may be comparative regular, or may exhibit complex contortions due to irregularity of flow during intrusion. Under the microscope (AM 24) the schistosity is less marked and the rocks do not differ greatly from the contaminated granites except that biotite tends to be grouped into linear aggregates. The minerals present and their interrelationships are the same as in the contaminated granites. In some sections (AM 20) a little muscovite is present.

D. *The lit-par-lit Intrusions of Aplitic Granites.*

So many supposed cases of lit-par-lit intrusion have afterwards been shown to be phenomena of metamorphism that it is of importance to record that there is little doubt in the present instance. At the northern end of Green Island the exposures are particularly good. In general the granitic veins follow the bedding of the mica-schist closely, swelling out in places into apophyses, in other places thinning to a mere streak or dying out entirely. At the northern end of Green Island there are several cases where the veins coalesce to form an intrusion of laccolithic or tree-laccolithic form. The intrusive veins vary in thickness but in typical cases (see Plate XXVII, Fig. 2) average about a foot, with the intervening bands of schist roughly the same thickness.

Petrologically the veins are comparable in appearance and composition to the reaction borders already described as surrounding the xenoliths in the contaminated granite. Where the veins swell out or coalesce into large intrusions the rock approaches the intrusion gneiss or contaminated granite in composition and appearance One vein, at the north-western end of Green Island, was studied in some detail. A specimen taken from the centre of the vein where it was about 15 inches across is almost completely devoid of dark minerals. In thin section (AM 49) it is almost indistinguishable from AM 30 except that no epidote or biotite is present. It has been suggested above that the granite-aplite between the xenoliths and granite is the result of an exchange of material between the granite and the xenolith. The nature of the granite-aplite of the veins in the lit-par-lit injection suggests that the same process has been in operation. Although in the field the junction between the aplite veins and the mica-schist appears sharp, the microscope shows that the junction is a closely welded one and only marked by the appearance of lines of biotite flakes. A specimen (AM 56) taken 6 inches from the vein mentioned above showed, in thin section, alternating bands of comparatively coarse aplite and fine-grained biotite schist.

Similar aplites occur mixed with the muscovite pegmatites on the mainland (AM 65), and the presence of muscovite in some supplies a connecting link with the pegmatites.

E. *Muscovite-Pegmatites.*

The highest veins in the series are muscovite pegmatites and quartz veins. The pegmatite veins fluctuate in width like those of the aplites (see Plate XXVII, Fig. 1) and frequently pass from one level to another, though in general following the bedding. The veins are, as a rule, coarse grained in the centre, consisting of large crystals of muscovite in a matrix of quartz, and finer grained towards the edges. They are best seen just at Amherst Point, immediately to the west of the Pagoda which is built out to sea on a reef. The country rocks are comparatively little altered and comprise soft biotite schists. A slide (AM 66) from the finer grained edge of one of the veins was seen to consist of roughly equal proportions of muscovite and quartz, with a little acid plagioclase (showing wavy albite lamellae) and a little microcline. The muscovite, as is frequently the case, had an extended period of crystallization and large flakes are fringed with smaller flakes. Contortion of the muscovite flakes is frequent. The rock has a few grains of spinel. The quartz veins do not call for any particular notice.

F. *Biotite and Biotite-Hornblende Schists.*

The xenoliths have been described above, and it remains to note the features of the country rocks from which these xenoliths have been derived and into which the intrusive masses have been forced. As mentioned already, the metamorphism is progressive in intensity. In the region characterized by lit-par-lit intrusion the country rock is a hard, fissile mica schist. A typical specimen from the eastern side of Green Island (AM 53) in thin section shows alternating bands of (*a*) a coarse mosaic of quartz and felspar, (*b*) a finer mosaic of the same minerals with the addition of biotite, magnetite, apatite, and epidote. In other cases, as in Pagoda Bay, a notably amount of hornblende may be present (AM 60 and AM 57). In all cases, however, hornblende is relatively less abundant than in the xenoliths.

Where the metamorphism becomes less intense the rock becomes

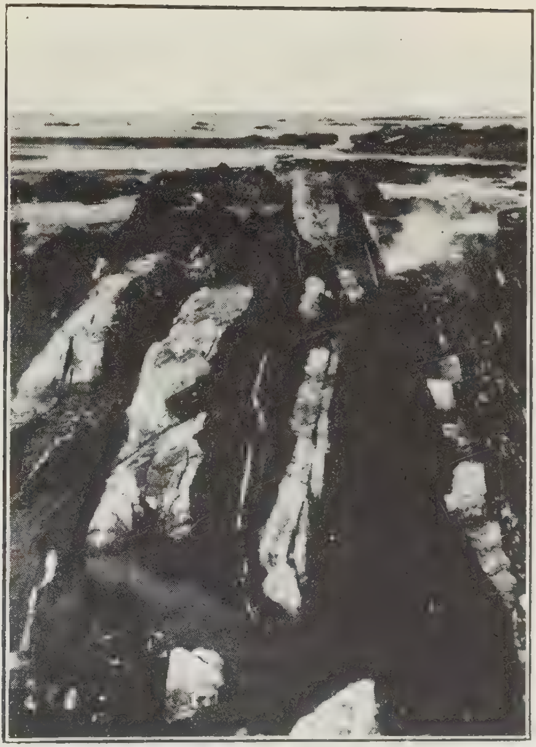

FIG. 1.—VEINS OF MUSCOVITE PEGMATITE IN BLACK MICACEOUS SHALES, 100 yards west of Pagoda Point, Amherst.

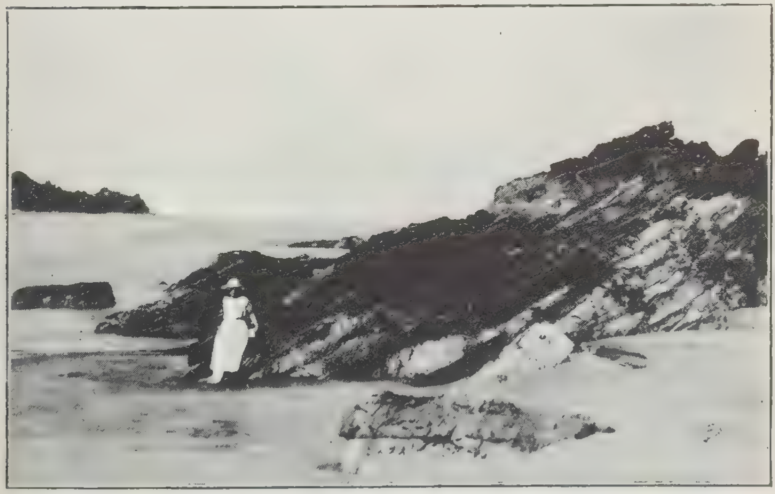

FIG. 2.—LIT-PAR-LIT INTRUSION OF GRANITE APLITE INTO HORNBLENDE-MICA SCHISTS, southern end of Pagoda Bay, Amherst Coast. Green Island in the distance.

softer. The rock splits along bedding planes which are marked by flakes of mica, but the rock is too soft to section. As the metamorphism becomes less marked the mica disappears and the stage of soft black or grey shales is reached.

IV. TECTONICS.

Judging by their lithology the country rocks at Amherst belong to the great "Mergui Series" which covers enormous areas in Lower Burma.[1] The age of the series is unknown, but is generally presumed to be Pre-Cambrian. The numerous granite masses which are found intruding the Mergui Series in Tavoy and Mergui (Lower Burma) are also of unknown age, though evidence, gradually accumulating, tends to point to a late Mesozoic age. The area under consideration is part of what is generally known as the Indo-Malayan system of mountains, the main folding of which is pre-Tertiary, though rocks as late as early Jurassic are known to be involved. The granite masses of Tavoy are regarded by Coggin Brown and Heron (op. cit.) as later than the main folding since they do not show signs of having been subjected to great strains. In the present case, however, the writer considers the micropetrography of the igneous rocks proves conclusively that the whole complex has been subjected to severe earth movements since intrusion. It is considered that movement *during* intrusion is insufficient to explain the universal presence in the igneous rocks of undulose extinction in felspars, contortion of muscovite flakes, and general mylonization.

Small faults are numerous in the field: though no attempt has been made to study the faulting in detail, it is obvious that dip faulting is very common. Apart from this, the rocks do not appear greatly shattered in the field, and huge masses of granite occur without a joint. Taking all things into consideration it is possible therefore that extensive earth movement immediately before the final stage of crystallization of the large masses might explain the observed features. In other words the intrusions of Green Island and the Amherst coast are associated with the main period of folding of the Indo-Malayan System and consolidated before the folding ceased. Thus the igneous masses are probably late Mesozoic.

V. SUMMARY.

1. The igneous complex shows a remarkably complete series of types from ordinary biotite granite, through contaminated granite, intrusion gneisses, lit-par-lit aplitic intrusions, to aplites and muscovite pegmatites.
2. Pale-coloured reaction zones occur between xenoliths and the granitic masses. The evidence points to an exchange of material between xenoliths and the surrounding magma.

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[1] Brown and Heron, "Geology and Ore Deposits of Tavoy": *Mem. Geol. Surv. India*, 1923.

3. All the rocks are mylonized and it is suggested that the microstructure can only be explained by movement during the final stages of crystallization. The folding is believed to have taken place in late Mesozoic times, as the area forms part of the Indo-Malayan Mountain System.

Magmatic Activity and Mountain Folding in the Andes of South Mendoza.

By HELGE G. BACKLUND, The University, Upsala.

INTRODUCTION.

IN a series of memoirs by Burckhardt (1),[1] Groeber (2), and Gerth (3), the stratigraphical sequence and structure of the Cordillera of South Mendoza has been lucidly described. On the basis of these memoirs, of my own field observations (12). and of the study of the large collection of rocks made by Dr. Gerth, I shall attempt in this paper to give a picture of the magmatic evolution of this part of the Cordillera of South America (35 to 37 degrees south latitude).

Two major cycles of magmatic activity have been distinguished :—

1. The pre-Andine magmatic cycle, *and*
2. The composite Andine cycle (five minor cycles).
   - (*a*) Dogger-Malm.
   - (*b*) Upper Cretaceous.
   - (*c*) Lower Tertiary.
   - (*d*) Middle Tertiary.
   - (*e*) Upper Tertiary.

It has been further established that every regional tectonic movement of the earth's crust in the Andine area has culminated in magmatic activity, a conclusion that is in accordance with, and thus strengthens, the hypothesis developed by W. Penck (8) as a result of his important work on the Puna of Atacama.

Each cycle of magmatic activity is represented by series of both effusive and intrusive rocks. The members of any series which are a consequence of identical geotectonic events are here described as *equivalent* ; in their typical representatives they closely agree in chemical and mineralogical composition. The members of a series which have penetrated the crust as a result of slightly differing phases of the same crustal movement may differ among themselves in chemical and mineralogical composition ; these members, abyssal and hypabyssal on the one hand, and effusive on the other, are said to be *correlated*. Each series, corresponding to a distinct orogenic movement, and including various diaschistic dyke-rocks and alkalic and other differentiates is referred to as a *clan* (= *Stamm*, German), all the members of a clan having a common parent magma.

THE PRE-ANDINE CYCLE.

The pre-Andine cycle, which is incompletely known, owing to the presence of widespread coverings of younger rocks, is represented by a common granite. This abyssal rock cuts through crystalline schists, metamorphosed polymict conglomerates, laminated claystones and yellowish quartzites. The latter are devoid of fossils, but their lithological composition strongly resembles the Permian glacial deposits described by Keidel (4) from the Sierra de la Ventana, and Pillahuincó (south of the Province of Buenos Aires), and by Keidel (5) and Hausen (6) from various localities north of Mendoza.

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[1] Figures in parentheses refer to List of References at end of paper.

As correlated effusive members of this cycle, genetically connected with the late or post-Permian granite, I interpret the mighty pile of lavas which in the Cordillera goes under the name of the *older porphyritic* (= andesitic) *formation*; with these lavas, poor in mafic minerals, are associated agglomerates, conglomerates, and tuffs. The age of the whole formation is post-granitic, since its basal conglomerate reposes on the eroded top of the granitic intrusion; and it is further known to be pre-Liassic. Contrary to previous descriptions, I consider this great Triassic formation as having been built up under nearly land conditions, because small erosional unconformities are frequent, and in the upper parts conglomerates occur at intervals.

The last member of the pre-Andine cycle is an olivine-bearing gabbroidal diabase, occurring in dykes cutting through both granite and "porphyrite". The basaltic or effusive equivalent of this diabase is now nearly all eroded away from the upper surface of the "porphyritic" formation. As already stated by H. Gerth (7), this upper surface itself underwent strong erosion before the next sedimentary strata were deposited. The close of the pre-Andine cycle was consequently characterized by substantial emergence, marking an upheaval or positive movement of the earth's crust.

THE ANDINE GEOSYNCLINE.

After the above-mentioned denudation of late Triassic times, the Andine geosyncline of Mendoza and Neuquén developed by downthrow, downwarp, submergence, and undatory movement generally, and culminated during Liassic times (Rhaetic ?) in an extrusion of spilitic (or ophiolithic) lavas, whose members are represented by albite-diabase and quartz-keratophyres. The intrusive equivalent is a soda-granite, though not of a pronounced alkaline type, associated with a monzonite as a basic differentiate. Both of these cut through the Triassic "porphyritic" formation and the late Permian granite, but they seem to be somewhat older than the effusive spilites.

The development of the geosyncline appears in this early stage to be still influenced by the tracks of older tectonic movements. The intrusions are elongated in a north-westerly direction, and along this direction the effusives also trend as a parallel ribbon of lavas. They mark the ancient Hercynian border of the Brazilian massif, and make an angle of from 45 to 60 degrees with the later Andine trendlines. In later stages the further development of the andine cycles is affected only locally by this posthumous Hercynian trench.

As to the pre-Andine cycle there is nothing known concerning the thickness of the Palaeozoic sediments which formed a cover to the late Permian granite. In the case of the Andine cycles and their associated granitic intrusions more information is available. The thickness of the sedimentary cover in each case of granitic intrusion varied from 400 to 1,000 metres. Where the cover was thin the granitic rocks have a hypabyssal or porphyritic structure. In certain Cretaceous intrusions this type of structure has also been observed where the rocks are covered only by correlated lava-sheets and tuffs. The lithological sequence of the sedimentary pile with its unconformities and conglomerates, and its beds of gypsum of three different ages (Oxfordian, Middle Cretaceous, and Upper Cretaceous-Tertiary boundary) gives a perfect conception of the alternation of great vertical movements during the Mesozoic and Tertiary Eras.

Succession of Clans.—A lengthy discussion of the methods of discriminating the various clans on the basis of the mineralogical and chemical composition of their different members (12) has led to the following conclusion. The application of Bowen's reaction principle to the evolution of the mafic minerals proves that the latter cannot always provide a reliable criterion. But since the rocks representing each clan are feldspathic, plagioclase being on an average about 60 per cent by volume, the feldspar may be the only true indicator of the clan and its parent-magma composition. It is found that equivalent rocks of the same clan may contain a plagioclase feldspar with nearly identical calcium proportions throughout.

To attempt an explanation of the mechanics of intrusion we may first suppose a roughly gravitational stratification of the elongated magma basin that underlay the Andine region. During the early stages of the revolutionary orogenic movement the hanging walls above the basin or cauldron are plunged more deeply into the heavier deeper-seated and hotter magma until a break-in of the roof allows an outburst of the magma to occur. Owing to the accumulated energy, the first magma to escape forces its way through to the surface; that is to say the effusive member of a clan comes first into position. Then after a short period of local gravitational settling with possibly slight inversion or other modification of the pulsating movement, intrusion comes into action, the available energy being now reduced, and the resulting rocks being the product of a higher, lighter and more gaseous portion of the magma basin.[1]

The correlated intrusive member of the clan (generally later, but sometimes earlier) consequently represents a more acid composition, and its plagioclase feldspar has therefore a lower calcium content than that of the correlated lavas.

The upper, lighter part of the basin being thus exhausted, the

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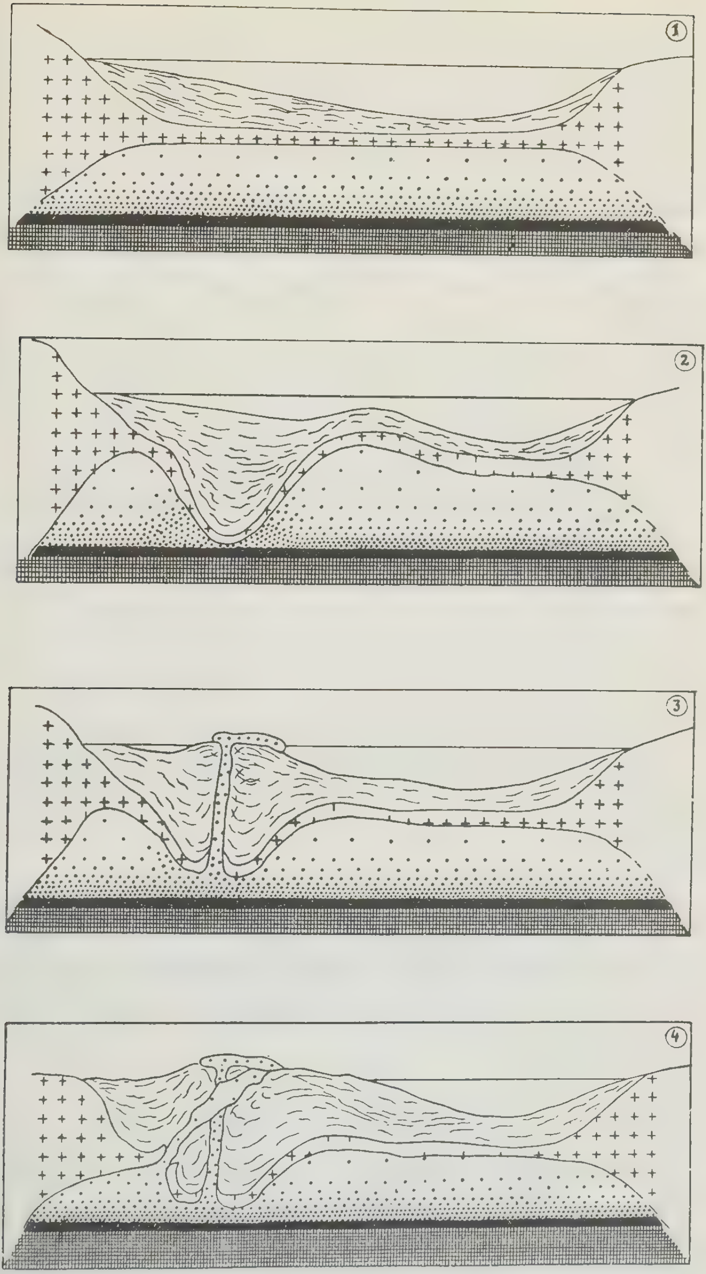
[1] Development may sometimes occur in the opposite direction—i.e. the intrusion of the lighter portion being the earlier—cf. diagram Fig. 1—as shown by certain field observations.



FIGS. 1–4.

next tectonic phase promotes a further sequence of activity in the same general order. But as the time interval between the first and the succeeding phase is too short to allow of a regional gravitational settlement of the magma, it follows that the succeeding clan is as a whole of more basic composition than its predecessor. The plagioclase feldspar of its members is more anorthitic, though a similar difference between the correlated abyssal and effusive members is found to obtain as before, the range, however, being perhaps less extensive (see Table II, p. 418).

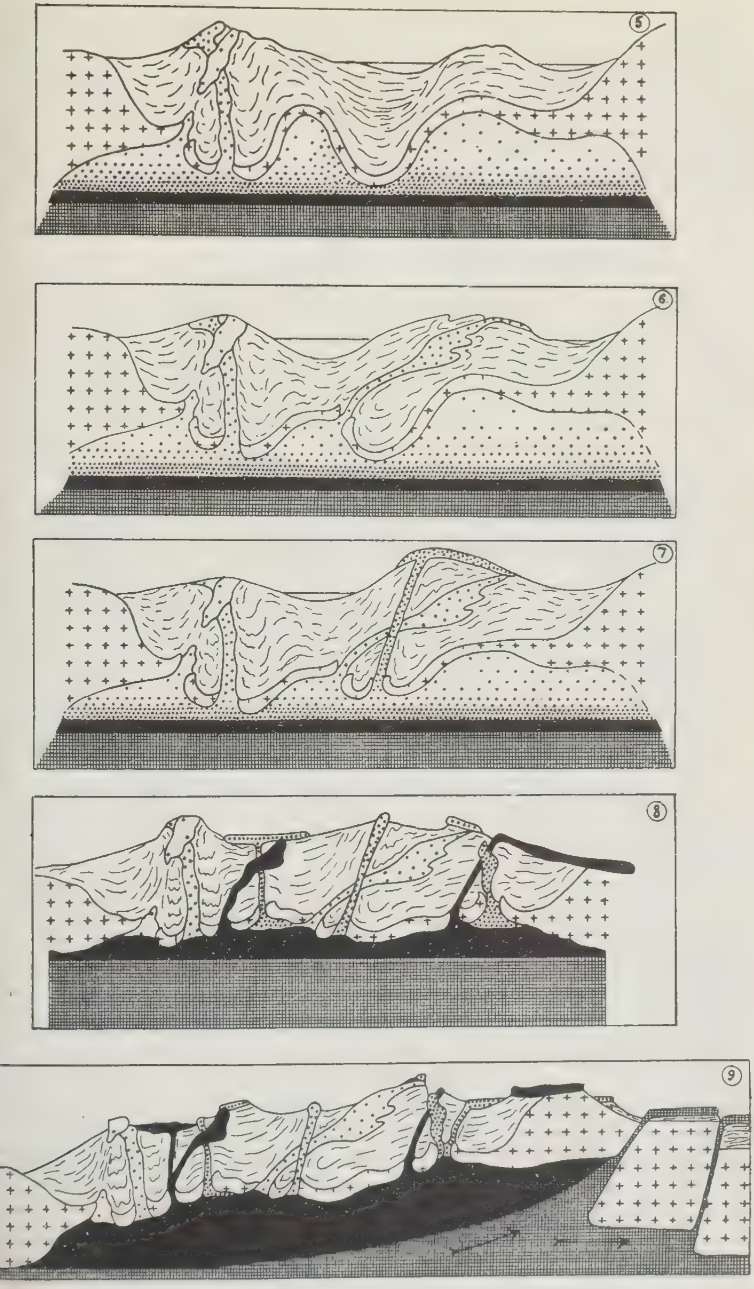
The evolution of each clan may end with a basaltic extrusion, particularly in the case of the still later phases. While the first two processes outlined above result in the tapping of widely contrasted parts of the differentiated magma, deeper parts of the basin may later begin to rise, the end of one cycle thus producing an even more basic type of rock than the beginning of the next. Owing to continued liquefaction and expansion of the underlying magma (due to lessening of the pressure) the basaltic extrusions from the deeper portions are accompanied by a widespread upheaval.

As the tectonic phases succeed one another and strip after strip of igneous products is added to the folded range, the evolutionary scheme outlined above for each clan becomes more and more inhibited owing to the rising rigidity of the crumpled crust. Thus the correlated members of the later clans gradually converge in petrological type, and approach the basaltic type. At the same time the intrusions, from being nearly concordant at the beginning of the series of clans, tend to become more and more discordant, finally culminating in gabbroidal necks.

Sometimes effusive representatives of the intrusive members of a clan have reached the surface. These are the equivalent members, and in chemical and feldspathic composition they are closely connected with the deep-seated facies of the same clan. They cut through and flow over their own correlated basic members and thus contribute to the diversity of the lavas.

The above conclusions are not invalidated by the presence of diaschistic and segregational dykes (in the German sense) because these represent pathological types, generated by exceptional local conditions involving volatile fluxes and assimilation. Even alkaline basic rocks, rich in potash and younger than the correlated extrusives, appear in some clans as the result of exceptional tectonic conditions (basanites, trachydolerites, essexites, luscladites, banakites, etc.). For these the feldspar rule does not hold, though taken as a whole they follow the general chemical trend of their own clan.

Following the Liassic spilites (already mentioned as associated with the evolution of the Andine geosyncline in its first stages) the true revolutionary or orogenic movements began in Dogger-Malm time, and continued in successive phases during the Upper Cretaceous and the Lower, Middle, and (?) Upper Tertiary. Later on, accumulating field evidence may more closely determine the



FIGS. 5–9.

epochs of these phases. At present it seems that the Lower and Middle Tertiary phases are nearly coincident, and it is difficult to discriminate between the correlated abyssal rocks of the two corresponding clans. But otherwise the rock sequence and the clan sequence as now determined are firmly established. The Dogger-Malm clan is only partly represented on the Argentine side of the igneous belt, but the correlated abyssal rock has been found by Felsch (9) on the Chilean side. The five phases, moreover, are by no means all of equal intensity, those of the Tertiary marking the culminating points.

Rock-content of clans.—From all that has been said above it will be clear that great stress has been laid on the mineral assemblages of the rocks, and especially on the feldspar determinations. On the other hand little stress is laid on rock names for the purpose of this preliminary survey, and rocks occurring in different clans may thus receive the same names. This clearly indicates the need for more names to be applied to " Pacific " types in an evolutionary series, and particularly in the andesitic correlated facies, as already pointed out by Lacroix (10).

At this stage, however, it has not been thought desirable to introduce new terms. Consideration of the term *basalt* suggests that this name should on no account be based on the content of olivine or extremely basic plagioclase in a feldspar-pyroxene rock, but that it should be restricted to rocks of ophitic texture with prevailing mafic minerals, i.e. to post-orogenic extrusions of plateau-basalts. The term *basalt* has here been used (12) for certain rocks occurring with the correlated young andesites only because in earlier publications they were so described. As we have seen, the whole magmatic evolution tends towards the basic pole as already recognized by W. Penck (11), but this evolution is only of local importance as a final episode, and cannot be regarded as having the universal significance ascribed to it by Penck who suggested a general desilicification of the " world-magma ".

The weak point of the arrangement of the rocks in clans is that not all the rocks are of accurately known stratigraphical position, especially those of the deep-seated rocks which have obscure relations. But though some of the rocks may be of uncertain association, they could be placed in one or other of neighbouring clans without any disturbance of the main conclusions. The fixing of the age of the extrusions and the intrusive sheets offers fewer difficulties.

The table (I) on the adjoining page gives an idea of the types of rocks occurring in the successive clans which have been evolved during the post-Liassic tectonic cycles of the Andes of Mendoza.

This table is based on a detailed investigation of 146 different rocks and on an examination of several hundred thin sections (12). The terms in brackets are of rocks having uncertain relationships, or of rocks that are not characteristic of their position in the classification (either in petrological type or in their *mis-en-place*).

Members of Clan.	(*a*) Dogger-Malm.	(*b*) Upper Cretaceous.	(*c*) Lower Tertiary.	(*d*) Middle Tertiary.	(*e*) Upper Tertiary.
I. Deep-seated rocks.	— [Granite ?]	Granodiorite. Tonalite. Aplodiorite. Adamellite.	Adamellite. Aplodiorite. Quartz-diorite. Quartz-hornblende-diorite.	Diorite. Windsorite. Quartz-augite-diorite. Quartz-diorite.	Olivine-norite. Quartz-augite-diorite. Hornblende-diorite. Granogabbro.
II. Correlated effusives.	Santorinite (Becke). Shastaite.	Labradorite-porphyrite (bandaitic).	Hornblende-andesite. Hypersthene-hornblende-andesite. [Hornblende-basalt.]	Pyroxene-andesites [Basalt].	Pyroxene-andesites. Hornblende-andesites [Basalts]. Cordierite-andesites [Basalts].
III. Equivalent effusives.	Dacite (ungaitic).	Masanite. Biotite-dacite. [Tonalite-porphyrite].	— [Quartz-diorite-porphyrite].	— [Quartz-diorite-porphyrite.]	Dacites (bandaitic). Hypersthene-augite-dacite. [Hornblende-diorite-porphyrite.]
IV. Dyke rocks.	[" Melaphyr " ?]	Kersantite. Vogesite. [Aplite.]	Spessartite. Ossypite. Kersantite.	Spessartite. Odinite. [Diorite-aplite.]	Spessartite. Vogesite. Augite-kersantite.
V. Alkali-rocks.	Nepheline-basanite.	Essexite (Luscladite).	Trachydolerite.	Trachydolerite. Sodalite-bostonite.	Banakite.
VI. Post-orogenic basalts.	" Melaphyr."	—	[Pampa-basalt ?]	[Pampa-basalt ?]	Pampa-basalt. (Plateau-basalt.)

The variation of the mean plagioclase feldspar in the typical members of the clans is shown in the following table (II), the figures of which refer to the percentage of anorthite.

TABLE II.

Members of " clan ".	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
I (+ III) Abyssal rocks and effusive equivalents.	(24)	33	43	46	60
II " Correlated " effusives.	42	54	58	66	60

The convergence within the fifth clan (*e*) of abyssal rocks and correlated effusives is evident, and also the steady increase from clan to clan of the anorthite content in the feldspars of homologous rocks. The feldspars of the rocks listed under headings IV, V, and VI (Table I, p. 417) do not follow this evolution in general, because in those rocks feldspar is neither the dominant mineral nor the general indicator of the magma composition.

As to the Pampa-basalts, which are true plateau-basalts, ophitic in texture, olivine-bearing, and containing a purplish pyroxene, their exact age is still uncertain. It seems that in different parts of Patagonia, which is the country of plateau-basalts *par excellence*, these basalt flows are not only of different ages, but that the intensity of the post-orogenic evolution (accompanied by general upheaval) for cycles (*c*), (*d*) and (*e*) varied in different sectors of the Andes. This being so, the Pampa-basalts may correspond to the post-orogenic evolution of any one of these three cycles, but more especially to the last one.

Basalts in the broader sense are also met with in those parts of the Cordillera that became rigid at earlier dates. Their outbursts were accompanied by block movements (cf. diagram, Figs. 8 and 9). But it may be that outbursts of true plateau-basalts are situated outside the main mountain range, because the growing thickness of the range prevented extrusion of this far-coming magma within its borders.

The post-orogenic plateau-basalts flowed down the region of epeirogenic uplift following ancient broad and shallow valley-floors away from the Andes. Since then the landscape has undergone inversion, the sedimentary formation of the valley slopes having been eroded more quickly and more deeply during each epoch of uplift. The more resistant basalt flows have thus come to remain as cappings to tabular mountains of circumdenudation exactly as in the cases I have already described from Northern Siberia (13).

Regional distribution of clans.—The gradual rigifaction of the mountain range step by step as a result of the five cycles of tectonic

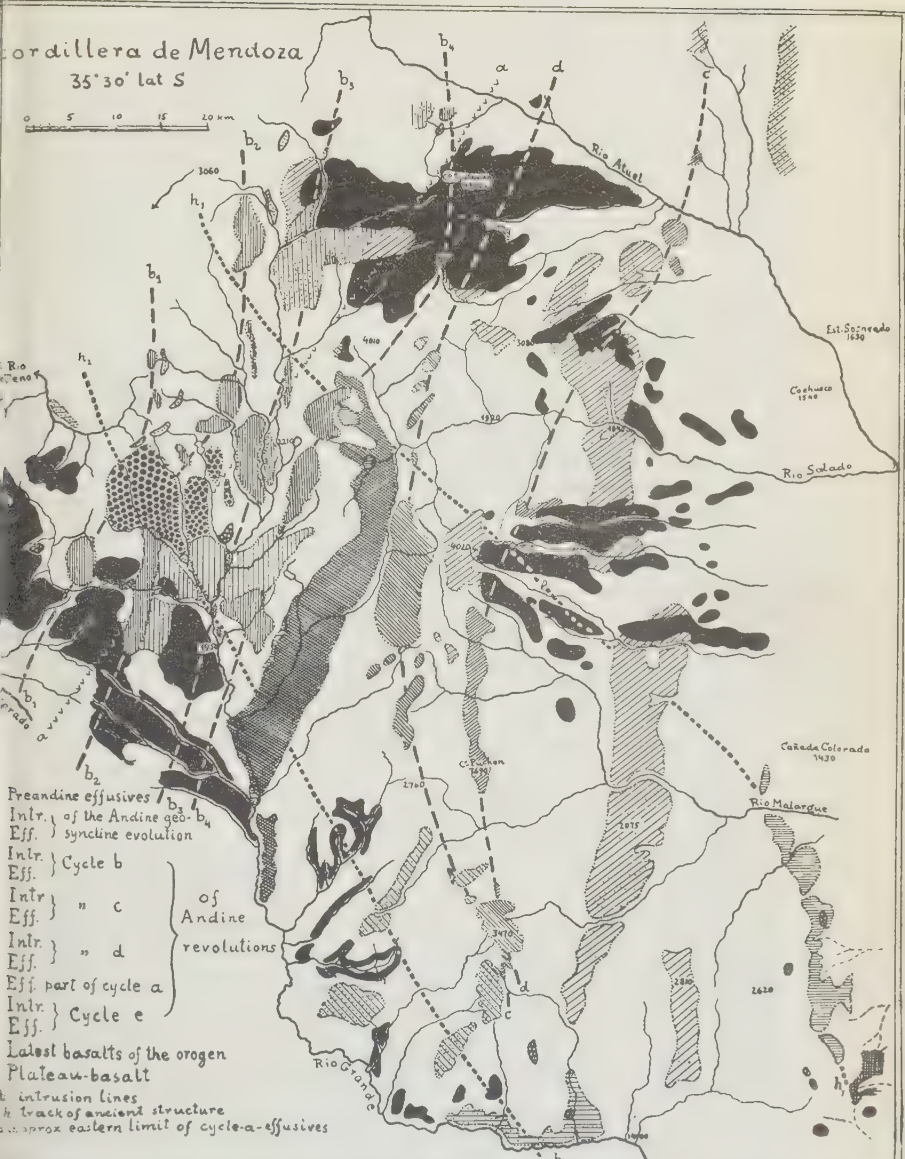

ordillera de Mendoza
35° 30' lat S
0 5 10 15 20 km
b4
a
d
c
b3
b2
b1
h1
h2
3060
Rio Atuel
Rio Teno
4010
3080
1920
2210
Est. Sosneado 1630
Cochusco 1540
Rio Solado
4020
1950
rado
a
C. Puchon 3690
2700
Cañada Colorada 1430
Rio Malargue
2075
3470
2810
2620
Rio Grande
Preandine effusives
Intr. } of the Andine geo-
Eff. } syncline evolution
Intr. } Cycle b
Eff.
Intr. } " c
Eff.
Intr. } " d
Eff.
Eff. part of cycle a
Intr. } Cycle e
Eff.
of Andine revolutions
Latest basalts of the orogen
Plateau-basalt
intrusion lines
track of ancient structure
approx eastern limit of cycle-a-effusives

FIG. 10.

and igneous activity is revealed by the linear distribution of laccoliths or phacoliths in the direction of the main Cordillera. The belt of clan (*a*) lies along the Chilean border; the Upper Cretaceous clan (*b*) follows to the east of the older one and is represented along four or five virgating lines; while still further eastward follow the two older Tertiary clans, (*c*) and (*d*), each arranged along slightly divergent lines. The *mis-en-place* of the last clan (*e*) is peculiar. The deep-seated rocks belonging to it are irregularly dispersed as necks over the whole area of block movement (cf. Fig. 9), as though they had been able to penetrate the solidified mass only with great difficulty through positions of relative weakness. Corresponding with the disposition of the earlier clans, the folding also advanced in the course of time from west to east, that is in the direction of the foreland.

The question remains whether each of the five tectonic cycles began with a spilitic facies, corresponding to each initial subsidence, as we have seen was the case at the culmination of the main subsidence in Triassic times. It would seem that the submergence preceeding each minor cycle differed from that of the Liassic geosyncline in being too shallow and too restricted in time to permit a similar magmatic accompaniment. Perhaps the configuration of the geosyncline and the thermodynamic conditions were no longer favourable to a spilitic facies after the first of the minor cycles.

Looking back to the pre-Andine cycle it is quite evident that it too was associated with a similar though possibly incomplete clan of igneous rocks.

Conclusions.—As a result of our present knowledge it is established that the igneous activity associated with the Andine tectonic cycles of the Cordillera of Mendoza began with isolated extrusions of spilites and intrusions of soda-granites and monzonites as their abyssal equivalents.

The five minor cycles themselves are characterized by granodioritic abyssal rocks and quartz-free andesitic effusives. These rocks are correlated and are characteristic of each orogenesis. Dacitic (quartz-bearing) rocks play a lesser and somewhat unimportant rôle as surface equivalents of the granodiorites. Dyke rocks are also insignificant, and the basic alkaline rocks that appeared towards the end of each orogenic cycle are infrequent. The major orogenic cycle, as shown most conspicuously by its closing phase, concludes with basaltic eruptions and gabbroid intrusions. The post-orogenic evolution following each cycle, and especially the last one, takes place with extrusions of plateau basalts accompanied by a general uplift.

Throughout the five minor cycles which make up the great Andine composite cycle the granodiorites and their equivalents evolve step by step, or phase by phase, towards a basic pole (somewhat rich in potash), that is, towards a grano-gabbroidal facies. So also do the andesitic correlated rocks but at a more basic level throughout.

As already pointed out by Steinmann (14) the widespread importance of the andesites in the Andes suggest that the above conclusions may be valid along the whole range. The vast areas of andesitic lavas and granodiorites of different ages in the orogenic zones of other mountain ranges (Caucasus, Urals, Persian ranges, etc.) invite attention with a view to further generalization and further detail. Unfortunately it may be very difficult elsewhere to elucidate the connexion between abyssal and surface activities as completely as has been possible in the vast and deeply eroded regions of the Andes. It is to be expected, moreover, that the number of orogenic phases within a main tectonic cycle may vary widely from place to place.

A glance at the older (Palaeozoic) folded mountain ranges gives a hint of the presence there also of different clans, together with the curiously isolated introductory spilitic action. But I do not wish to suggest either that every spilitic action has necessarily been a forerunner of orogenic cycles, or vice versa.

Comparison between the Andes and the Caledonian ranges of Scandinavia disclosed radical differences, due perhaps to a different rhythm in movement. The exposed sections in Scandinavia are much deeper than those of the Andes, and are obscured by a great bulk of metamorphic rocks, of which the primary nature is still uncertain. But even here further investigations (15) seem likely to lead to at least general analogies with the generalizations achieved for the Andes of Mendoza.

Acknowledgments.—Finally, the author presents his sincere thanks to Messrs. P. G. Roeber (of the Argentine Geological Survey) and H. Gerth (of Leiden) for valuable discussional contributions of their field experiences in the Andes, and to Prof. Arthur Holmes (of the University of Durham) for his amiable revision of the typescript.

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DESCRIPTIONS OF FIGURES.

Figs. 1–4.—Successive stages in the evolution of the first minor cycle (*a*).

Figs. 5–7.—Successive stages in the evolution of the second minor cycle (*b*).

Fig. 8.—The final minor cycle (*e*) of convergent magmatic evolution.

Fig. 9.—The post-orogenic evolution of the major Andine cycle, illustrating: epeirogenic uplift of the orogenic belt (on the left) with irregular penetration by basaltic necks; and block movements beyond the orogen (on the right) accompanied by widespread plateau eruptions.

In the above diagrammatic sections the lithosphere is represented by crosses and the superincumbent sediments by broken lines. The magma basin is shown below, the density of shading indicating the gradation from granitic to basaltic magma. The deeper plateau basalt magma is indicated by cross-hatching.

Fig. 10.—Map of the Cordillera of South Mendoza, Argentine, showing the distribution of the intrusive rocks and their correlated extrusives (in part after a field-map by Dr. H. Gerth ; sedimentary formations omitted).

The Mica-Lamprophyres of Wigtownshire.

By H. H. Read, D.Sc.

Introduction.

The Geological Survey has recently formed a very extensive collection of the dyke-rocks of Galloway.[1] This collection was made mainly by Mr. Robert Eckford, and, to a less extent, by Mr. Wm. Manson. One or more specimens were taken of practically every dyke shown on the original 6-inch field-maps. Since there are over 500 collected dykes in Wigtownshire alone, the size and importance of this collection is apparent. A dyke-suite of this magnitude, so thoroughly collected without the personal bias of the petrographer, supplies unique material for study. By the kindness of Sir John S. Flett, F.R.S., Director of H.M. Geological

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[1] Note.—This series of dykes has been fully collected with the object of verifying the index-letters attached to the outcrops as shown in the new colour-printed maps which are in course of publication. Dr. Read has furnished the names of the rocks.—J. S. Flett.

Survey, I have been permitted to investigate that part of the collection coming from Wigtownshire. This Wigtownshire portion consists of considerably over 1,000 rock-specimens, nearly 200 of which have been sliced. In this present paper I propose to give an account of the distribution and petrography of one group —the mica-lamprophyres—of the Wigtownshire dyke-rocks.

THE WIGTOWNSHIRE DYKES.

Examination shows that the Wigtownshire dykes fall into two great divisions. All except seven belong to the calc-alkalic series; the remaining seven are definitely alkalic.

The small alkalic group of dykes will not be considered in this investigation. These dykes are uniform analcite-dolerites, and, since a typical representative cuts the Permian rocks of Stranraer, may be taken to be of Tertiary age.

The great series of calc-alkalic dykes penetrates folded Ordovician and Silurian strata. The dykes vary from purely felspathic rocks to lamprophyres of various kinds; they include representatives of such calc-alkalic groups as porphyrites, malchites, spessartites and kersantites. This suite is the dyke-phase of the Galloway Province of Lower Old Red Sandstone age; the plutonic phase of this province is provided by the Galloway " granites ".

The Wigtownshire dykes are for the most part shown on the newly issued colour-printed Sheets 1, 2, 3 and 4 of the Geological Survey 1-inch map of Scotland. They have been briefly mentioned in the old Explanations[1] to these Sheets, whilst a short account by Sir J. J. H. Teall[2] of the dyke-rocks of the Galloway Province as a whole is to be found in the memoir on the Ordovician and Silurian rocks of the Southern Uplands.

I. THE MICA-LAMPROPHYRES.

Distribution, Size, and Trend.

The most important result from this study of the first group of the Wigtownshire dyke-rocks is the recognition of the localization of the mica-lamprophyres to a definite belt of country. There is no well-expressed clustering of the Wigtownshire dykes as a whole. They are most abundant for half a dozen miles along the coast south of Port Patrick; an isolated cluster of a dozen dykes is seen at Juniper Rock, 7½ miles northwards from Port Patrick, whilst the " granite " mass of Kirkcowan, 5 miles west of Newtonstewart, is attended by a group of over thirty dykes. Apart from these attempts at clustering, the dykes would be seen to be fairly uniformly distributed in a section from Mull of Galloway to Port Patrick or from Burrow Head to about Wigtown.

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[1] Explanation of Sheet 1 (1872), pp. 7–8; Sheet 2 (1873) pp. 7–8; Sheet 3 (1873), pp. 20–21; Sheet 4 (1878), pp. 19–20.

[2] " The Silurian Rocks of Britain: vol. i, Scotland," *Mem. Geol. Survey*, 1899, pp. 625–31.

When, however, one leaves the distribution of the dykes as a whole and takes up the distribution of the mica-lamprophyres one recognizes an interesting fact. All the mica-lamprophyres occur south-east of a line which runs, with the strike of the sediments, from a point on the west shore of Wigtown Bay due east of Kirkinner south-westwards to Port William; it is continued immediately to the north-west of the Mull of Galloway. This line, together with certain figures of the dyke distribution, are shown in Fig. 1. When the statistics of the dyke occurrences are examined, this localization of the mica-lamprophyres is clear. The total number of Wigtownshire calc-alkalic dykes examined is 505. Of these, 183 occur south-east of the Mull—Port William—Kirkinner line, and the remaining 322 north-west of this line; but whilst there are sixty-eight mica-lamprophyres south-east of the line, not one has been collected from the north-west side. Whatever be the explanation of this line it marks the limit of the mica-lamprophyres with considerable abruptness for even in the small Mull of Galloway area there are eleven mica-lamprophyres amongst the collected dykes, whilst beyond the line not one has been found. Whether this line extends north-eastwards across Scotland and south-westward into Ireland is a

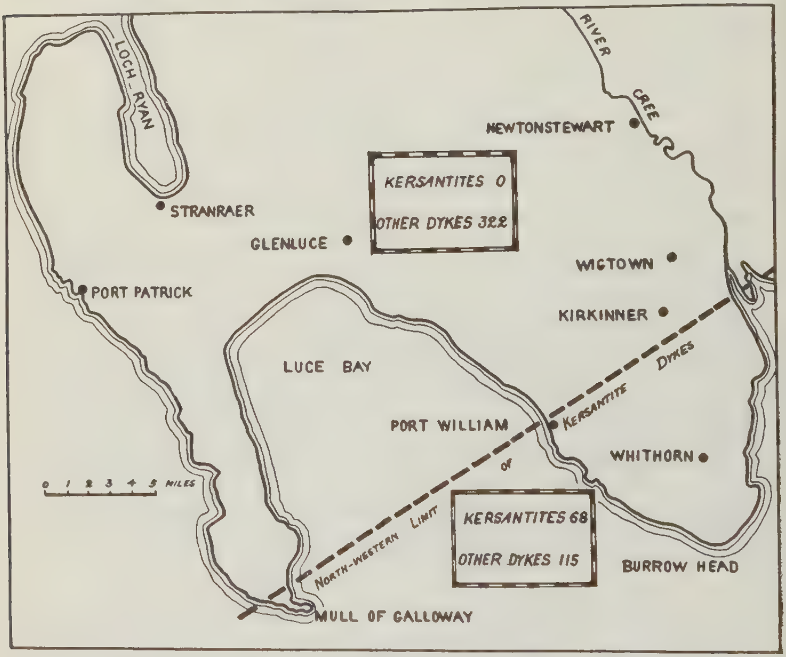

FIG. 1.—Sketch-map showing the Distribution of the Wigtownshire Kersantites.

question for future investigation; its significance can be realized only in connexion with the other igneous rocks of the Galloway Province.

On the original 6-inch field-maps of the Geological Survey approximate details of the thicknesses of the mica-lamprophyre dykes are given for fifty-five of the sixty-eight dykes of this group. This information may be summarized as follows:—

Thickness.	*Number of Dykes.*
1 ft. and under	12
2 ft. to 1 ft.	15
3 ft. to 2 ft.	13
4 ft. to 3 ft.	3
5 ft. to 4 ft.	4
6 ft. to 5 ft.	7
10 ft.	1

It will be seen that forty of the measured dykes are under 3 ft. in thickness.

The dominant strike of the Ordovician and Silurian rocks of Wigtownshire is N.E.–S.W. The majority of the mica-lamprophyres coincides in trend with this direction, forty of the dykes being intruded parallel to the strike of the country rocks. Of the remaining dykes of which details are available nineteen cut definitely across the strike of the sediments; these dykes have various trends, but the majority agree more or less with the dominant N.E.–S.W. direction. A very few dykes have a N.W.–S.E. or N.N.W–S.S.E. trend. It may be said, then, that the dominant trend of the mica-lamprophyres is N.E.–S.W., i.e. the direction of the strike of the Caledonian folding; these dykes, together with the other Wigtownshire dykes, mark a zone of tension that arose as a reaction to the compression-forces of the Caledonian movement.[1]

PETROGRAPHY.

In colour the mica-lamprophyres are dark grey, often with a tinge of brown or green. Glistening black mica plates, pale green pyroxene columns and a few round pinkish felspathic areas are observable in most hand-specimens. As usual with this group, the rocks are much decomposed; they weather with a thick reddish or pale-grey sheath.

The main constituents of the Wigtownshire mica-lamprophyres have been plagioclase, biotite, augite and probably olivine, with accessory quartz, orthoclase, apatite and iron-ore. The mica-lamprophyres are thus *kersantites*.

The *plagioclase* is dominantly of lath-shaped habit; large plates or shapeless grains are of rarer occurrence. There is occasionally a suggestion of subradiate grouping of the laths. Albite, pericline and Carlsbad twinnings are common. In composition, the felspar is an acid oligoclase with a mean refractive index varying, in different dykes, from 1·53(7) to 1·54(0). Zoning is but poorly developed.

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[1] Cf. J. W. Evans, Anniv. Address, Geol. Soc. Lond., 1925, *Q.J.G.S.*, vol. lxxxi, 1925, p. lxxxvi.

The dark *mica* is the typical lamprophyre biotite. Single crystals sometimes reach a size of 5 cms. In slice, it gives distorted hexagonal basal sections which are often clustered together to form the fortification-structure[1] seen in other Scottish and foreign lamprophyres. Longitudinal sections are often quadrilateral laths, but in some cases the side faces are wanting. Pleochroism is strong; it is $\mathfrak{c} = \mathfrak{b} =$ dark brown with tinge of green, $\mathfrak{a} =$ pale yellow, often almost colourless. Marked colour-zoning is seen; usually this is shown by a darker border only, but in many cases a dark brown central area is also present, whilst rarely several concentric bands of varying tint occur. In certain basal sections the darker central area is of perfect hexagonal form. G. Linck[2] considered the marginal darkening of the biotite of an Alsatian minette to be due to magmatic corrosion, whilst other observers have suggested internal bleaching. There seems no reason, however, to question the original character of the colour-zoning in the Wigtownshire cases. The mica is practically uniaxial. It alters to chloritic products and is often split by calcite lenses. Good sagenitic webs have been noted.

Unaltered *pyroxene* has not been observed, but pseudomorphs after undoubted crystals of pyroxene are of very common occurrence (see Fig. 2B); they reach 1 cm. in length. In transverse section these have a regular octagonal form with prism and pinacoidal faces equally developed; in longitudinal sections good terminal faces are visible. The original pyroxene has been replaced by chloritic and carbonate products. Sometimes tiny biotites, presumably original inclusions, are seen arranged in regular fashion within the pseudomorphs. Certain lozenge-shaped pseudomorphs suggest the original presence of *olivine*; these are now formed of chlorite with much iron-oxide dust, or of carbonate and iron-oxide—the pilitic alteration appears to have been rare. Both olivine and pyroxene pseudomorphs are occasionally rimmed about by biotite laths.

Of the minor components, there may be noted *apatite* in abundant needles, black *iron-oxide* in euhedra, and interstitial *quartz*. *Ortho-*

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[1] Cf. G. Linck, " Geognost.-petrog. Beschr. des Grauwackengebietes von Weiler bei Weissenburg " : *Abhandl. zur Geol. Specialkarte von Elsass-Lothringen*, Bd. iii, Heft i, 1884, p. 25. J. S. Flett, " The Geology of Carn Chuinneag, Inchbae, etc." (explanation of Sheet 93) : *Mem. Geol. Survey*, 1912, p. 121. H. H. Read, " The Geology of Strath Oykell and Lower Loch Shin " (Explanation of Sheet 102) : *Mem. Geol. Survey*, 1926, p. 169.

[2] G. Linck, " Ueber ein neues Vorkommen von Minette in Weiler bei Weissenburg " : *Mitth. Geol. Landes-Untersuch. Elsass-Lothringen*, Bd. i, Heft ii, 1887, p. 70.

clase may be present in some quantity in all slices, but its definite detection is a matter of difficulty. In a few rocks it forms shapeless areas often intergrown with quartz, but such rocks show a texture different from that of the plagioclase-rich kersantites proper. There is no doubt that by far the dominant felspar in these rocks is plagioclase. The structure of the kersantites is the panidiomorphic-granular of Rosenbusch, the quartz and doubtful orthoclase being the only anhedral minerals. Approaches to the holocrystalline porphyritic structure are provided by the occurrence of very large crystals of biotite and pyroxene but, as repeatedly stressed by P. J. Bejer,[1] for similar rocks from Lausitz, Saxony, there are all gradations in size between these so-called phenocrysts and the smallest crystals of the rock. Biotite appears to have begun crystallization at a very early period.

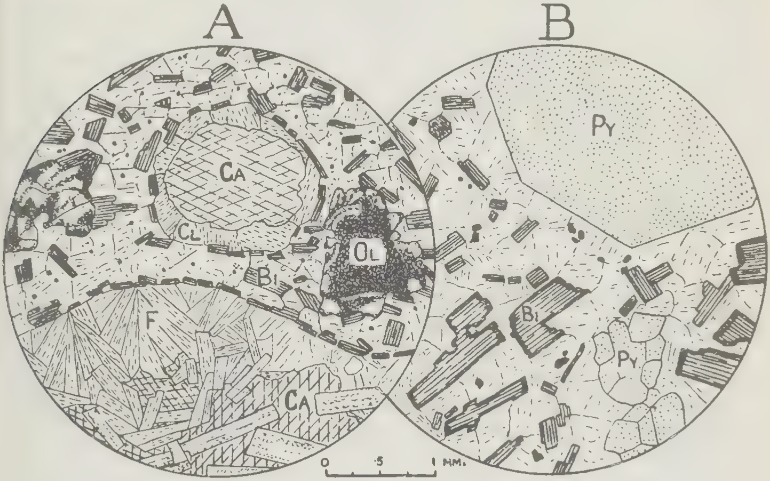

Fig. 2.—Wigtownshire Kersantites.

A. Kersantite with ocelli. F=plagioclase, Ca=calcite, Cl=chlorite, Bi=biotite, Ol=altered olivine. 1,100 yards NNE. of Physgill House, 2½ miles SSW. of Whithorn.

B. Kersantite. Py=pyroxene, Bi=biotite. 300 yards S.15° W. of Slate Heugh, 3¼ miles S.W. of Whithorn.

These kersantites occasionally show in perfection the ocellar structure often described in the lamprophyres. Scattered through the rock are small rounded bodies which give circular or oval sections. These bodies, manifestedly all of similar origin, consist of various minerals (Fig. 2A). In a common case, large euhedral plagioclase prisms project from the rim into the interior of the sections, the central parts of which are filled in with a little quartz and large plates of calcite. Often the felspar laths are definitely radial, sometimes they diverge from two points within the section, whilst in many cases they show no arrangement at all. Other bodies have their centres formed of large grains of calcite bordered by a narrow chlorite zone and this by a quartz zone. In practically every example biotite laths are arranged tangentially around the sections and often form a continuous rim—this produces the ocellar structure.

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[1] P. J. Bejer, " Beiträge zur Kenntnis der Kalkalkalireihe der Lamprophyre im Gebiete des Lausitzer Granit-lakkolithes ": *Neues Jahrb.*, B-Bd. xl, 1916, p. 583.

Ocelli have been repeatedly described from many types of lamprophyres but they appear to be especially abundant in the mica-traps, as shown by such names as Kugelminette, minette globuleuse, Perlkersantit. They have been explained in several ways.[1] Cohen[2] considered certain Odenwald examples to be an endomorphic contact-effect, but later work has shown that the distribution of ocelli is not necessarily a marginal phenomenon. Rinne[3] has described and figured beautiful examples in his "Perlkersantit" from Kiautschou, and has explained them as concretions in a solidifying magma, the coating of biotite laths being an effect of the surface-tension of the supposedly slightly viscous magma-drops. Hussak[4] gives figures of typical ocelli in the leucite-tephrites of Brazil and explains[5] them as partly pseudomorphs of the groundmass after leucite crystals, partly pseudomorphs of analcite after leucite and partly due to a combination of these two causes. Hussak cites the icositetrahedral form of certain of his ocelli in support of his view, but it must be pointed out that, as is to be expected, this form can be simulated very closely in any rock in which the tangential biotite plates reach a fairly large size. Linck[6] has described ocelli exactly like those of the Wigtownshire kersantites from the minettes of Weiler, Alsace, and comes to the conclusion that they are of drusy or amygdaloidal origin. A similar explanation has been given for Scottish examples by Mr. J. B. Hill[7] and by Sir J. S. Flett.[8]

In the Wigtownshire kersantites the ocelli are best explained as due to the infilling of vesicular cavities, and their history is probably somewhat as follows. Biotite was crystallizing in the dyke magma when, possibly at the intrusion-act, gas bubbles were formed which, as they increased in size with decrease of pressure, pushed aside the biotite plates causing these to arrange themselves on the surface of the bubble. These cavities were afterwards in places partly filled with quartz and felspar of the still fluid groundmass and still later completely filled with carbonate and chloritic materials which were probably of magmatic origin. The mode of origin, then, of the more particularly ocellar part of this structure, i.e. the tangential arrangement of biotite laths, is the same as that of the more usual ocellar structure proper in which the pushing aside of the biotite laths is done by crystals of later growth.[1] Such types of ocellar structure have been noted above around augite and possibly olivine crystals. The occurrence of calcite and chlorite filling vesicular cavities in the kersantites suggests that in large measure the ubiquitous decomposition of the mica-lamprophyre family wherever found may be due to the action of juvenile agencies.

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[1] Rosenbusch, *Mikros. Physiogr.*, II, i, 1907, p. 665.

[2] E. W. Benecke and E. Cohen, *Geognostische Beschreibung der Umgegend von Heidelberg*, 1879, pp. 148–77.

[3] F. Rinne, "Beitrag zur Gesteinskunde des Kiautschou-Schutz Gebietes": *Zeitschr. d. Deutsch. Geol. Gesell.*, vol. lvi, 1904, pp. 154–6, figs. 14 and 15.

[4] E. Hussak, "II Über brasilianische Leucitgesteine": *Neues Jahrb.*, ii, 1892, pp. 151–5, figs. 3, 5.

[5] E. Hussak, "III Nochmals die 'Leucitpseudokrystall'-Frage": ibid., p. 159.

[6] G. Linck, "Geognostisch-petrographische Beschreibung des grauwackengebietes von Weiler bei Weissenburg": *Abhandl. zur Geol. Specialkarte von Elsass-Lothringen*, Bd. iii, Heft i, 1884, pp. 36–8.

[7] J. B. Hill, "The Geology of Mid-Argyll" (Explanation of Sheet 37): *Mem. Geol. Survey*, 1905, p. 109.

[8] J. S. Flett, "The Geology of Upper Strathspey, etc." (Explanation of Sheet 64): *Mem. Geol. Survey*, 1913, p. 83. "The Geology of Blair Atholl, etc." (Explanation of Sheet 55): *Mem. Geol Sur.*, 1905, p. 121.

In no case is a Wigtownshire kersantite sufficiently fresh to justify the expense of a chemical analysis. In future comparative work connected with this study of the Wigtownshire dykes I propose to use the analysis of the kersantite of Oberlichtenau near Königsbrück in Lausitz, Saxony. This rock has been analysed, described and figured by P. J. Bejer[2]; it appears to be exactly like the Wigtownshire augite-olivine-kersantites.

There was probably little original variation amongst the Wigtownshire kersantites although the varying stages of decomposition have produced secondary differences. The type is a *pyroxene-olivine-kersantite* with large and abundant pyroxenes, and even those, the most abundant, kersantites in which only poor indications of the original presence of pyroxene and olivine are available, probably departed very little from this type.

* * * * *

It may be concluded that these kersantites form a definite and quite well-defined type of Wigtownshire dyke-rock; in Wigtownshire they do not occur to the north-west of the line, Mull–Port William–Kirkinner.

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[1] Cf. H. Rosenbusch, *Mikr. Physiog.*, II, ii, 1908, p. 976.

[2] Loc. supra cit., pp. 597–8, 650, pl. xiii, fig. 3.

REVIEWS.

A Group of Red Measures or "Coloured Strata" in the East Glamorgan and Monmouthshire Coalfields. By A. Howell and A. H. Cox. Proc. South Wales Inst. Eng., vol. xi, 1924, pp. 139–74, with 4 plates.

IT is not usual to notice in this Magazine papers in British journals, but in this case an exception may perhaps be allowed, since few geologists probably read regularly the publications of the societies devoted specially to coal-mining, and the facts here detailed are of special stratigraphical interest in correlating the Upper Carboniferous deposits of South Wales with the well-known "Red Beds" of the Staffordshire and North Midland Coalfields. The authors here describe a series of some 300 feet of red and variegated strata presenting a marked resemblance to the Etruria Marls of the Potteries, lying below the Pennant Sandstones of South Wales, which are the equivalents of the Newcastle and Halesowen Sandstones.

The red and variegated strata here described under the name of the Deri series are found at a small depth, usually about 30 ft., below the Brithdir seam at the base of the Pennant or highest subdivision of the Staffordian or Transition series of this area. They consist of different varieties of red, blue, purple, and subordinate green grits and marls, with occasional bands of sandstone, conglomerate, shale, and occasional thin coals and fireclays. The thickness of the series varies from 270 to 400 feet, and it can be traced from east to west for about 14 miles and from north to south for some 10 miles, appearing along the northern outcrop of the coalfield east of the Taff, but disappearing about 4 miles south of the latitude of Pontypool.

The occurrence of this isolated patch of red strata among the more normal sediments of the South Wales coalfield is of much interest in its relation to the general conditions of deposit of coal in this and the neighbouring areas, especially the Forest of Dean and North Somerset. It forms an instance of a patch of "red" strata in actual continuity with the "black" type, and in this case Triassic staining appears to be definitely excluded, as explained by the authors.

Handbook of Cornish Geology. By E. H. Davison B.Sc., F.G.S. pp. 103, with 1 plate, 6 figures, and a map. Penzance, 1926.

MR. DAVISON, who is head of the Geological Department of the School of Metalliferous Mining at Camborne, Cornwall, has long been known as one of the leading authorities on the geology of that extraordinarily interesting county, and by his knowledge of the subject from both the scientific and economic standpoints he is well qualified to write the standard book on the subject. In this volume, which is published by that enterprising body, the Royal Geological Society of Cornwall, we have therefore an authoritative exposition of the leading features of the geology of that area, greatly condensed, it is true, but nevertheless covering in an effective manner all the main points.

Cornish geology is simple in one way, because it is hardly at all troubled by palaeontological problems but its petrology is of extraordinary interest, and has thrown a flood of light on the processes of granitic intrusion and the differentiation of magmas, the progress of pneumatolysis, and the formation of ore-deposits. These deposits have been in the past, and are likely to be again in the future, of great importance in the world's markets. It is at present difficult to see how civilization can get on without tin, and as the rich alluvials of other regions get used up, lode-mining must eventually be the chief source of this metal: the future of tin-mining seems now to lie with Cornwall and Bolivia.

The work of Davison, Cronshaw and Dewey on Cornwall is in entire agreement with the generalizations of Spurr in America on the sequence of ore-deposits, and has led already in the able hands of the technical advisers of the larger mining companies to developments in the Camborne-Redruth area, which are likely to be of first-class importance in the history of English mining, and their future progress will be watched with the greatest interest.

But this book is by no means confined to the problems of tin-mining: on the contrary it gives a clear and interesting account of the general geology of the region, and as is only natural, considerable space is devoted to china clay, the key industry of the St. Austell district. The descriptions, though short, are clear and interesting, and a very useful feature is a section of some ten pages devoted to a list of localities where good exposures or striking phenomena are to be seen. There is also a good bibliography, and the book should be of the greatest value to visitors to Cornwall and to geologists in general.

PETROLEUM IN UGANDA. Geological Survey of Uganda. Memoir No. 1. By E. J. WAYLAND. pp. 60, 4 maps, 22 illustrations. Entebbe, 1925.

THIS Report is noteworthy, not only for describing a most interesting occurrence, whatever else, of petroleum, but for containing much information concerning the geology of the Lake Albert section of the Central African Trough. In regard to the first point there is nothing to add to Mr. Wayland's guarded statements, but in regard to the general geology it is worthy of note that the old name of "Argillite Series", in general terms comparable to the Karagwe Series, has been resolved (as mentioned in *Nature* two years ago), into a lower Ankolian and an upper Mityana-Butologo Series, part even, at Entebbe, having been found to be of Karroo age. The relation of the Karagwe to the Ankolian Series may shortly be established. Passing into the Tertiary, the sediments of the Lake Albert Rift fall into two subdivisions, a lower probably of Miocene age, termed the Kisegi Beds and including the Karamoja Series, and an upper, the Kaiso Beds of Pliocene and Lower Pleistocene age, the two being separated by an unconformity due to movement during deposition. These, again unconformably, are overlain by the high level gravels and recent beds.

Detailed accounts are given of six areas concerned in the possibility of petroleum production, the composition and origin of the oil is considered, this being in turn followed by appendices dealing with more general subjects. Here Mr. Wayland touches on the controversial point of the compression as distinct from the tension theory, dwelling on the faulted mass of Ruwenzori as evidence of the former view. The elevation of the Kaiso Beds provides a measure of the late Tertiary movements, which are of great importance inasmuch as the formation of the Victoria Nile and a fall in the level of Lake Albert of at least 1,000 feet are concluded to be due to this agency.

The Report is as complete as possible and well furnished with maps and illustrations.

J. P.

GEOLOGICAL AND PETROGRAPHICAL STUDIES AROUND TIEFENSTEIN, SOUTHERN BLACK FOREST, GERMANY. By S. K. RAY. pp. 111, 14 plates. London: The Avenue Press, 1925.

THE region under study in this work comprises 60 sq. kilometres in the southern Schwarzwald, drained by the Alb from Vogelbach to the Rhine frontier. The rocks of the " Grundgebirge " include a metamorphosed sedimentary series (Rensch gneiss) and an eruptive series (Schapbach gneiss). The latter is described as " completely metamorphosed ", but this statement appears to be little more than conjecture, and no evidence is given which would preclude these rocks being referred to as primary gneisses. Hercynian activity is represented by small masses of amphibolite and anorthosite and the great mass of Carboniferous Albtal granite, with attendant intrusions of aplite, granite-porphyry, lamprophyres, etc. Special attention is devoted to the xenoliths found in the granite, the terminology of Lacroix for the *enclaves* of volcanic rocks being followed.

In the graphical treatment to which the rock analyses—ten new—are subject, this thesis faithfully portrays the paper gymnastics of the Zürich school.

C. E. T.